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LSSA LOW-COST SILICON SOLAR ARRAY PROJECT

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First ANNUAL REPORT

FOR THE PERIOD JANUARY 1975 - MARCH 1976

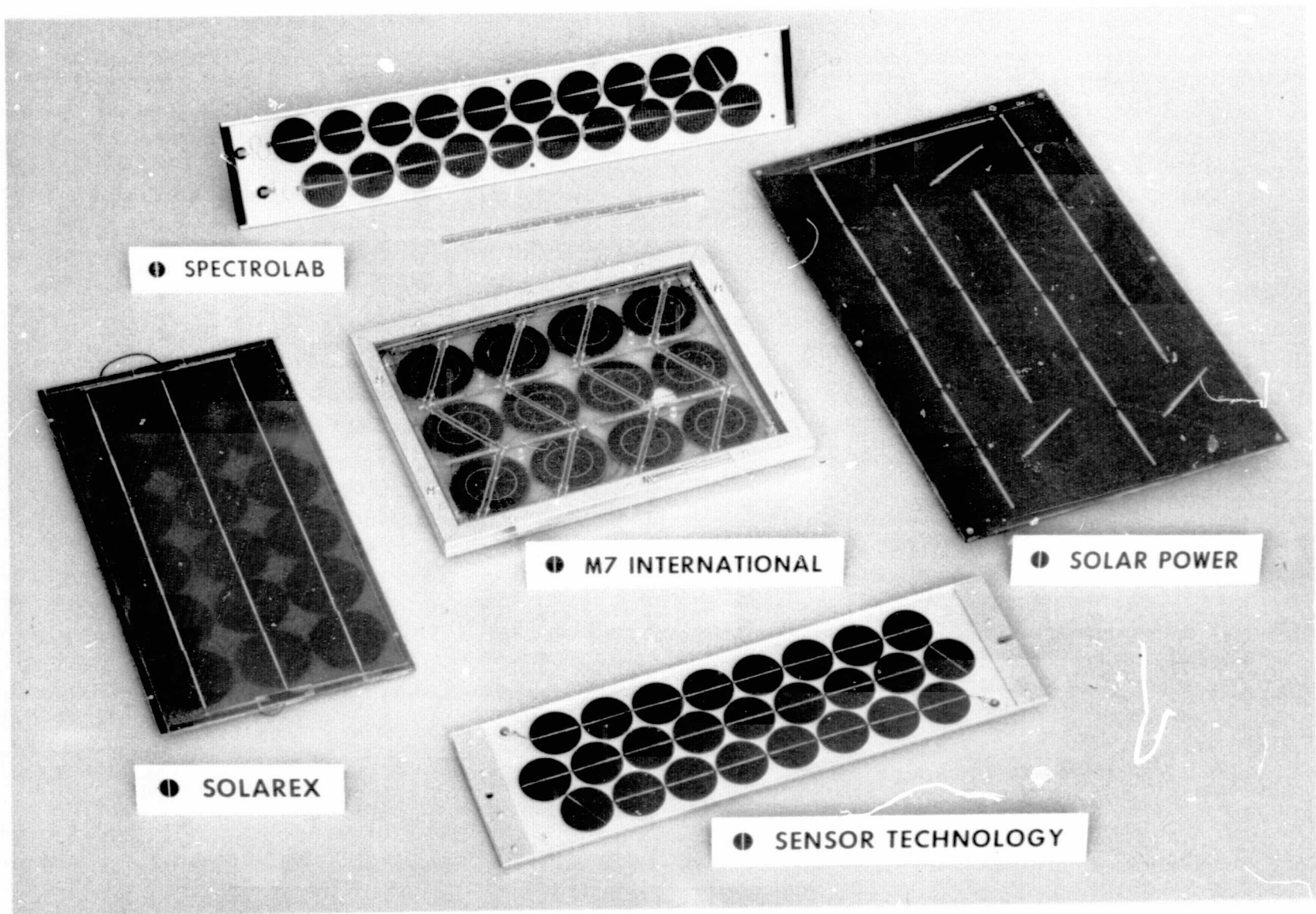
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FIRST ANNUAL REPORT
OF THE
LOW - COST SILICON SOLAR ARRAY PROJECT
—
FOR THE PERIOD
JANUARY 1975 - MARCH 1976

JPL Document 5101-3
Published - August 9, 1976

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA



Frontispiece. Forty-six kilowatts of the above modules are being delivered by the indicated manufacturers for test and demonstration purposes (see Part V, Large Scale Production Task)

ABSTRACT

In response to the need to find new methods of economically generating enough electrical power to meet future requirements, the Photovoltaic Conversion Program of ERDA's Division of Solar Energy was established in January 1975. The overall Program objectives are (1) to develop the technology for low-cost photovoltaic power and (2) to stimulate industry to produce, market, and distribute photovoltaic systems for widespread residential, commercial, and governmental use. The Low-Cost Silicon Solar Array Project (LSSA) was established at the Jet Propulsion Laboratory as part of the ERDA Program. Its goal is to greatly reduce the price of solar arrays by the improvement of manufacturing technology, by adaptation of mass production techniques, and by helping achievement of user acceptance. The Project's approach includes the development of technology, its transfer by industry to commercial practice, the evaluation of the economics involved, and the stimulation of market growth.

The activities and progress of the LSSA Project during its first year are described in this document. It is the first Project document intended for wide dissemination and is a report covering all Project activities, with primary emphasis on the technical plans and accomplishments. The development of manufacturing technology is now and will continue to be performed principally by industries and universities. To date, 24 contractors are working on new silicon-refinement processes, silicon-sheet-growth techniques, encapsulants, and automated-assembly studies. Nine more contractors have been selected to perform additional technology investigations and their contracts are being negotiated. Additional contracts will be issued in the future as promising ideas appear.

Industry, through investment in manufacturing and supplementary activities, is increasing its role in Project-supported activities. Five companies are manufacturing "off the shelf" solar arrays that are being purchased for ERDA's test and demonstration activities. Thirteen proposals, submitted in response to a Request for Proposal, are being evaluated for the procurement of a larger quantity of semistandardized solar arrays. Plans are being formulated for future purchases of increasing quantities of solar arrays manufactured with the evolving state-of-the-art technology and selling at decreasing unit costs.

The ERDA Program is derived from two decades of extensive research, development, and use of silicon solar cells by industries, universities, private organizations, NASA, NSF, and other governmental agencies. The Program plan now being implemented originated under NSF and was thoroughly reevaluated by ERDA in conjunction with industry and other government agencies and continues to be upgraded as the project evolves.

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FOREWORD

The activities and accomplishments of the Low-Cost Silicon Solar Array Project (LSSA) during its first year are described in this document. These activities are part of the ERDA Photovoltaic Conversion Program which is responsible for the national effort directed toward the development and utilization of entire photovoltaic power systems.

This report is the first Project document intended for widespread dissemination, and is primarily a technical report covering all the Project activities, with emphasis on the technical plans and accomplishments. The majority of the technical accomplishments relate to activities in the past three months, because the participating industries and universities have been under contract for only a few months. The report is arranged in a functional manner and is not strictly arranged as the Project is organized.

The Project will be issuing Quarterly Reports starting with the first report in May 1976. These Quarterly Reports and the future Annual Reports will emphasize the technical accomplishments achieved during their respective reporting periods.

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 LIST OF ABBREVIATIONS
General

CVD	chemical vapor deposition
DOD	Department of Defense
EBIC	electron-beam induced current
EDAX	energy dispersive analysis of X-rays
EFG	edge-defined film-fed growth
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
JPL	Jet Propulsion Laboratory
LASS	Large Area Silicon Sheet Task
LeRC	Lewis Research Center
LSP	Large Scale Production Task
LSSA	Low-Cost Silicon Solar Array Project
NASA	National Aeronautics and Space Administration
NSF	National Space Foundation
PA&I	Project Analysis and Integration Task
PADEM	Project Alternative Design Evaluation Model
RANN	Research Applied to National Needs
RFP	Request for Proposal
SAMIS	solar-array manufacturing industry simulation
USES	utility-owned solar-energy system

Chemical Symbols

Al	aluminum	Mg	magnesium
C	carbon	Mn	manganese
Cl	chlorine	Ni	nickel
Cu	copper	O	oxygen
Cr	chromium	Si	silicon
F	fluorine	Sn	tin
Fe	iron	Ti	titanium
H	hydrogen	V	vanadium
He	helium	Zn	zinc
I	iodine	Zr	zirconium

PART I

SUMMARY

Activities directed toward future widespread use of photovoltaic systems for the generation of electric power were initiated with the establishment, in January 1975, of the Photovoltaic Conversion Program of ERDA's Division of Solar Energy. The Program's activities are planned to develop and to promote the use of photovoltaic systems to such an extent that the private sector will produce and utilize cost-competitive photovoltaic systems. The ERDA Program plan is based on years of previous research, development, and studies. The objectives of the ERDA Program are:

- To develop low-cost reliable photovoltaic systems.
- To stimulate the creation of a viable industrial and commercial capability to produce and distribute these systems for widespread use in residential, commercial, and governmental applications.

The Low-Cost Silicon Solar Array Project (LSSA), a part of the ERDA Program, was established at JPL in January 1975. The LSSA Project goal is to reduce the cost of solar cell arrays by improving the technology and by increasing the solar array production capability and volume.

JPL's role in the ERDA plan is:

- To support silicon-solar-array manufacturing technology development and its transfer to industry.
- To encourage expansion of industrial capability to produce solar arrays.
- To support methods of promoting user acceptance.

The specific JPL Project goal for 1985-86:

- To reduce today's solar array prices of \$20,000 to \$25,000 per kilowatt in annual quantities of 100 kilowatts to less than \$500 per kilowatt in annual quantities of 500,000 kilowatts.

Progress toward the cost reduction goals achieved during the past year has been notable and has achieved the planned goals. The activities and accomplishments of the LSSA Project are summarized in this report.

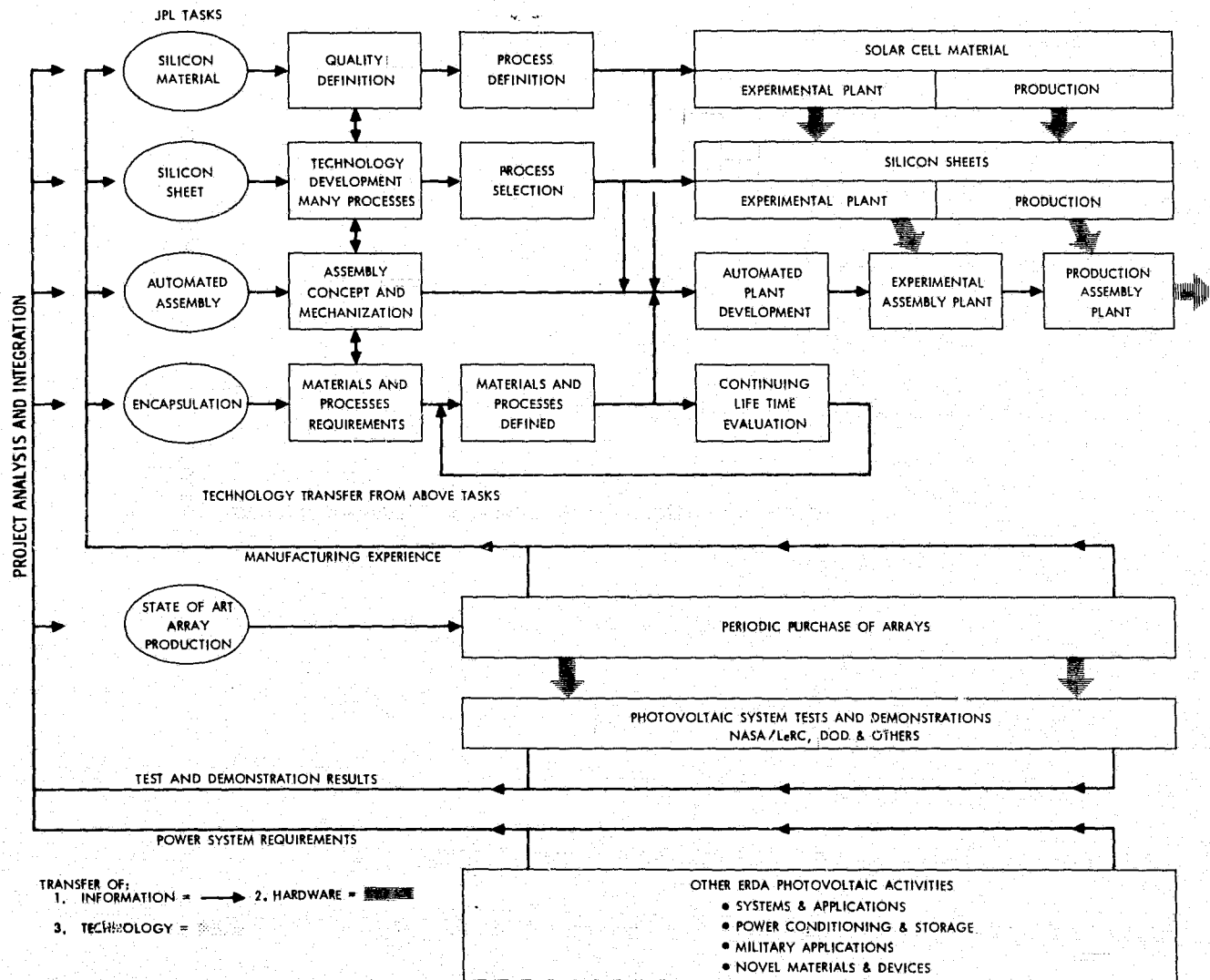
The approach being implemented to achieve the Project's objectives consists of technology development, industry involvement, commercialization, and market stimulation. Technology development is directed toward the extraction and utilization of those items from past and current research activities that can reduce the cost of producing solar arrays. Industry involvement is being fostered by participation in the technology development, by the transfer of technology to commercial practice, and by planned early large annual procurements of solar arrays. Market growth is being supported and stimulated by the annual solar-array procurements, by ERDA's photovoltaic power system tests, by operational and economic evaluations of these arrays, and by active participation with array users in defining requirements and designing arrays. The Project will conduct solar-array design and test activities and will manage and integrate the solar-array technology development activities.

Technology development involves the selection and support of potential solar-array manufacturing cost reduction efforts; continuing assessment of the technical feasibilities of the evolving techniques and hardware; and verification of the economic viability of new manufacturing processes. These activities are being accomplished principally by industries and universities and are divided into four tasks:

- 1) Production of low-cost silicon material.
- 2) Economical production of silicon in large-area sheets suitable for the manufacture of solar cells.
- 3) Development of economical encapsulation materials and techniques for array lifetimes greater than 20 years.
- 4) Development of automated processes and equipment for low-cost high-volume production of solar arrays.

The major steps to be accomplished by the four tasks and the interrelationship of these tasks are shown in Fig. 1-1.

The large-scale production activity involves the periodic purchase of increasing quantities of solar arrays at decreasing unit prices and with the latest state-of-the-art technology. The arrays are being procured from



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**Fig. 1-1. Functional relationships within the project and
between the Project and ERDA**

industry on a commercial basis to meet performance specifications and environmental requirements for use in ERDA photovoltaic power system tests and demonstrations. Hence, current technology will be evaluated under numerous and diverse environmental and operational conditions. This activity will stimulate an expansion of industry's solar-array manufacturing capabilities and demonstrate the resulting cost reductions. It will also measure the benefits of incorporating the latest photovoltaic technology and facilitate early detection of manufacturing problems. In conjunction with array manufacturers and users, data will be obtained for establishing design, reliability, and performance improvements of solar arrays. The functional relationships within the LSSA Project and between the Project and ERDA are shown in the preceding figure.

The project analysis and integration (PA&I) effort focuses on the planning, integration, and overall project analytical support which contributes to Project decision-making. This support will be implemented by providing assessments of possible performance and economic consequences of alternative Project plans, developing the interface requirements among the Project tasks, supporting the establishment of the interface requirements between the LSSA Project and other ERDA Photovoltaic Conversion Program activities, and by developing the plans and procedures for integrating the tasks within the Project and between the Project activities and other elements of the Program.

The Project approach of conducting parallel efforts within each of the technology development tasks and the large scale production activities provides for examination of alternative approaches in order to obtain the most cost-effective methods for achieving individual task objectives. Then, to optimize the overall project efforts, extensive examinations of the trade-offs between the task approaches are performed.

Considerable effort has been devoted to the Project in planning, implementing, and administering these widely diverse and complex procurement activities, involving universities, large industries, small businesses, and various governmental agencies. Many unsolicited proposals have been received and are being evaluated with additional ones anticipated on a continuing basis.

In addition to the contracted effort, JPL will utilize in-house expertise and facilities in technical assessment of the materials, devices, and processes which are being developed within the Project as well as conduct limited technology development.

The LSSA Project was initiated on January 9, 1975; the internal Project organization was established in accordance with JPL Program Plan 1200-181, dated November 15, 1974. An industry briefing was conducted on February 5, 1975 to introduce the Project plans, objectives, schedules, and details of related procurements. Approximately 300 persons attended, representing 105 companies and 15 universities.

A major effort during this first year has been to organize and coordinate this diverse technical activity. In addition to periodic individual contract reviews, the first Project Integration Meeting was held January 13 and 14, 1976 at JPL; technical representatives of all the participating organizations attended. Papers covering the Project activities were presented at the Second Semiannual Solar Photovoltaic Conversion Program Conference in Orlando, Florida by JPL representatives in January 1976. Contractor representatives also attended the conference.

A. PROJECT ANALYSIS AND INTEGRATION

Project Analysis and Integration supports planning activities by developing and implementing techniques for assessing Project plans and progress; by providing operational and economic analyses; by determining internal and external interface requirements; and by contributing to design requirements. These activities provide for the integration of Project tasks as well as integration of the LSSA Project with other elements of the ERDA Photovoltaic Program.

Project assessment methodologies continue to be formulated and applied to decision problems. Informal integration and interface meetings have been conducted with other elements of the ERDA Photovoltaic Program and the first formal LSSA Project/Task Integration Meeting has been held.

Operational and economic analyses are continuing under development: the USES (utility-owned solar energy systems) required-revenue model (developed jointly with ERDA and the Electric Power Research Institute) is being prepared for publication; the SAMIS (solar-array manufacturing industry simulation) is being evaluated at this time.

B. TECHNOLOGY DEVELOPMENT CONTRACTS

Request for Proposal (RFP) packages for the four technology development tasks were mailed in March 1975 to approximately 272 organizations. In response to these four RFPs 91 proposals were received by the end of April. The proposals were reviewed and evaluated on the basis of compatibility with the Project objectives, technical merit, and price competitiveness. Further clarifying information was obtained from the organizations that submitted the highest priority proposals either by visiting the organization or by having representatives come to JPL. Upon completion of these surveys, each task area was reviewed and guidelines were prepared with regard to the number of contracts that could be selected and the funding necessary to support these procurements. The final contractor selections were made by selecting the highest priority proposals to the extent permitted by the anticipated Project budget levels. Contractors were notified in the July - September period as to whether or not they had been selected. Notifications were made on the basis of the funding available to cover the contracts, on an obligation basis, and as consistent with the budget situation. Formal contract negotiations were initiated with the organizations shown in Table 1-1. Nine contracts were negotiated and signed by the end of October. The negotiation and awarding of many of the remaining contracts was delayed because of patent waiver requests and other factors.

C. SILICON MATERIAL TASK

The objective of the Silicon Material Task is to develop a capability for producing silicon, at a cost of less than \$10 per kilogram, that is suitable for the most economical fabrication of solar cells. At present, semiconductor-grade silicon is used for making solar cells. It is known that solar cells can be fabricated from less pure silicon; however, cell efficiency may be reduced

as the quantities of impurities increase. Therefore, solar cell performance versus silicon impurities and crystalline structure is being investigated. The evaluation of solar cell performance versus material/solar cell properties and cost can be verified only through years of analysis and testing. Consequently, parallel efforts are under way: (1) reduction of the production costs of semiconductor-grade silicon, (2) definition of a less pure, less costly solar-cell-grade silicon, and (3) development of an economical process to produce this solar-cell grade silicon. In evaluating the above processes a reduction in the consumption of energy required to produce the silicon is an important factor.

Processes that are being investigated with regard to their potential for the low-cost production of semiconductor-grade silicon are as follows: a method of processing SiH_4 , the reduction of SiCl_4 and SiI_4 , and a cyclic process using SiF_4 and metallurgical grade Si (see Table 1-1). Most of the accomplishments to date in the Silicon Material Task have been theoretical analyses and the preparation of experimental equipment. Some preliminary experimental results have been obtained. The definition of solar-cell-grade silicon will result from evaluations of materials and solar cells made from crystals in which the silicon has been doped with a variety of impurities. The crystals will be grown by the Czochralski, dendritic-web, and float zone methods. Many crystals of various compositions have been grown and sliced. The method of preparing solar cells from these slices has been standardized. Material and cell evaluation techniques and plans are being prepared. Potential solar-cell-grade processes that will be investigated are as follows: C reduction of SiO_2 using a plasma, use of C and SiO_2 in an electric arc furnace followed by purification steps, Na reduction of SiF_4 , reduction of SiCl_4 with alkali metals or H_2 using a plasma arc heater, and reaction of H_2 and SiCl_4 in a nonequilibrium plasma jet. These efforts are just starting. Supplementary studies of fluidized-bed technology and of the relative commercial potentials of the above processes are being conducted.

D. LARGE-AREA SILICON SHEET TASK

The objective of the Large-Area Silicon Sheet Task is to develop an economical method of producing large silicon sheets that can be inexpensively made

Table 1-1. Technology development contractors

Contractor	Technology Area
TASK 1. SILICON MATERIAL (11 contractors)	
<u>Semiconductor-Grade Silicon Production Processes</u>	
Battelle Memorial Institute Columbus, Ohio	Si from SiCl_4 or SiH_4
Motorola Phoenix, Arizona	Si using SiF_4 transfer
Union Carbide Sistersville, W. Virginia	Si from SiH_4
<u>Solar-Cell-Grade Specifications</u>	
Monsanto Research St. Louis, Missouri	Investigation of effects of impurities on solar cell performance
Westinghouse Electric Pittsburgh, Pennsylvania	Investigation of effects of impurities on solar cell performance
<u>Solar-Cell-Grade Silicon Production Processes</u>	
Dow Corning Hemlock, Michigan	Si from pure source materials using arc furnace processing
Texas Instruments Dallas, Texas	Si from C reduction of SiO_2 using plasma processing
Stanford Research Institute Menlo Park, California	Si by duplex vapor-electrochemical conversion of SiF_4
Westinghouse Electric Pittsburgh, Pennsylvania	Si by plasma-arc-heater reduction of SiCl_4 with H_2 and alkali metals as reducing agents
Avrami Research Laboratories Princeton, New Jersey	Si by use of a nonequilibrium plasma jet
<u>Commercial Potential of Processes</u>	
Lamar University Beaumont, Texas	Evaluate relative commercial potentials of Si production processes developed under Task 1
TASK 2. LARGE AREA SILICON SHEET (11 contractors)	
<u>Ribbon Growth Processes</u>	
IBM Hopewell Junction, New York	Edge-defined, film-fed growth
Mobil-Teco Waltham, Massachusetts	Edge-defined, film-fed growth
Motorola Phoenix, Arizona	Laser zone ribbon growth
RCA Princeton, New Jersey	Inverted Stepanov growth
Univ. of So. Carolina Columbia, S. Carolina	Web-dendritic growth
<u>Sheet Growth Processes</u>	
General Electric Schenectady, New York	Floating substrate (chemical vapor deposition on liquid)
Honeywell Floomington, Minnesota	Dip-coating (on low-cost substrates)
Rockwell Anaheim, California	Chemical vapor deposition (on low-cost substrates)
<u>Ingot Growth and Cutting</u>	
Crystal Systems Salem, Massachusetts	Heat-exchanger ingot casting and multiple wire sawing
Varian Lexington, Massachusetts	Breadknife sawing
Univ. of Pennsylvania Philadelphia, Pennsylvania	Hot-forming of silicon
Contract to be awarded in Spring of 1976.	

Table 1-1 (contd)

Contractor	Technology Area
TASK 3. ENCAPSULATION (4 contractors)	
Battelle Memorial Institute Columbus, Ohio	Encapsulant experience and definition of environment, encapsulant test methods and capabilities
DeBell and Richardson Enfield, Connecticut	Polymeric properties and aging studies
Rockwell Anaheim, California	Accelerated/abbreviated testing
Simulation Physics Burlington, Massachusetts	Bonded integral glass covers
TASK 4. AUTOMATED ASSEMBLY OF ARRAYS (7 contractors)	
Motorola Phoenix, Arizona	Manufacturing processes assessment
RCA Princeton, New Jersey	Manufacturing processes assessment
Texas Instruments Dallas, Texas	Manufacturing processes assessment
Simulation Physics Burlington, Massachusetts	Electron-beam solar cell fabrication
Mitre Corporation McLean, Virginia	Array test evaluation
Texas Instruments Dallas, Texas	Czochralski growth and wafering improvements
Solares Rockville, Maryland	Array test evaluation
Contract to be awarded in Spring of 1976.	

Table 1-2. Large-scale procurement contractors (5)

<u>In-EW Solar Array Procurement</u>	<u>EW</u>
M7 International Arlington Heights, Illinois	3
Sensor Technology Chatsworth, California	8
Solar Power Wakefield, Massachusetts	15
Solares Rockville, Maryland	10
Spectrolab Sunnyvale, California	10

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into solar cells with good electrical and physical properties. Contemporary solar cell fabrication requires the sawing of crystals into thin wafers with diamond saws followed by polishing. Approximately 75 percent of the crystal material is wasted. An ideal technique would be to grow crystalline sheet in a geometry that would require neither cutting nor polishing and yet would produce a material from which high efficiency solar cells could be fabricated. As yet, no one technique has been developed, and perfected that attains this ideal solution. However, the progress made in development work on a number of growth techniques has been sufficient to indicate that the ideal technique may be achievable. Consequently, many growth techniques are being analytically and experimentally investigated. Backup work on crystal ingot growth and advanced cutting techniques is also being performed (see Table 1-1). The initial work will emphasize determination of the technical feasibility of the various processes. The successful processes will then be evaluated for their economic feasibility. The following work is now being performed by Large-Area Silicon Sheet Task contractors:

- 1) Ribbon growth from a molten source based on (a) capillary action movement of material through a die (i. e., the EFG technique) and (b) gravity feed of material from an inverted die (inverted Stepanov technique).
- 2) Web-dendritic growth directly from a molten source with no shaping required.
- 3) Laser zone crystallization of ribbon material (ribbon-to-ribbon process).
- 4) Vapor deposition of thick film material on a low-cost substrate by chemical vapor deposition or other methods.
- 5) Sheet growth using novel techniques which include dip-coating, growth from a supersaturated binary melt, and static growth of large ingots.
- 6) Ingot cutting using multiple-blade and multiple-wire saws.
- 7) Characterization of materials obtained from the above R&D work in terms of their suitability for fabrication of high-efficiency (greater than 10 percent) solar cells. (An array efficiency of at least 10 percent is desired.)

In general, most of the activities to date in the Large-Area Silicon Sheet Task have been theoretical studies, the preparation of the experimental equipment, and initial growth experiments. Improvements in capillary die design have been achieved which resulted in a reduction in surface particle contamination of the silicon ribbon. A fast growth, edge-defined, film-fed growth (EFG) machine is in operation. Seed crystal structure experiments have yielded knowledge which potentially could result in more uniform crystal growth structure. Results to date, although very preliminary, are satisfactory and encouraging.

E. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop the capability to economically encapsulate solar arrays for a 20-year lifetime. Encapsulation materials must transmit a maximum amount of sunlight to the solar cells as well as protect the solar cells and electrical conductors from the detrimental effects of a variety of environmental conditions during the life of the arrays. They must be inexpensive and easy to process during mass production of the arrays. The encapsulant must be chemically stable over a range of temperatures, and resistant to fire, abrasion, impact, ultraviolet radiation, and microorganisms.

The first phase of the task effort will consist of a systematic assessment of:

- 1) Potential encapsulant materials based on past experience.
- 2) Definition of the environment.
- 3) Potential improvement of encapsulant materials and processes.
- 4) Test and analytical methods required to evaluate and verify material performance.

In the second phase a suitable encapsulant system will be developed and verified.

Literature research is being conducted to learn what past experience in the encapsulation of semiconductor devices has been. To date, more than 300 documents (out of an expected 600) have been reviewed.

The environmental analysis is based on nine sites, selected as representative extremes of United States climatological conditions. Climatic, insolation, and air pollution data from these sites are being analyzed to determine the rates of occurrence of combinations of conditions which may be detrimental to array lifetimes. Evaluation of accelerated/abbreviated testing methods has only recently started. As the information from items 1) and 2) becomes available, work on items 3) and 4) will commence. During the next few months additional contracts will be awarded, as originally planned (see table above).

F. AUTOMATED ASSEMBLY TASK

The objective of the Array Automated Assembly Task is to develop and demonstrate the process and equipment technology for the mass production of low-cost solar arrays. The plan is to study and assess present and potential production processes and techniques that are adaptable to solar array production; design automated production equipment; and stimulate expansion of solar array production facilities. Three companies have recently been awarded contracts to assess the current state-of-the-art technology and to identify those areas of solar cell technology which require development to achieve low-cost, high-volume production. Progress to date has consisted of each contractor organizing a team, submitting baseline cost estimates and plans, and making a preliminary evaluation of current semiconductor technology as it relates to the economics of solar cell manufacturing.

In response to an unsolicited proposal JPL has funded a contract with Simulation Physics to determine the potential offered by an improved process for producing high efficiency solar cells, at room temperature, at very high production rates. This process includes junction formation by ion-implantation and annealing of the junction damage by a beam of low energy electrons. After evaporation of the ohmic contacts and evaporation of an antireflective coating,

the solar cell is once again scanned by a beam of low energy electrons to sinter both the ohmic contacts and the antireflective coating to achieve maximum bonding strength. The results to date are encouraging.

G. LARGE-SCALE PRODUCTION TASK

An RFP for 40 kilowatts of "off the shelf" solar arrays from several manufacturers with existing facilities and proven designs was issued in July 1975. The RFP requested information in regard to current designs being produced, quality control procedures, product field experience, and a nominal 5 watt, 9.5 volt module design. Six proposals were received in August. The proposals were quite varied in many respects - including costs, which ranged from moderate to high. In order to establish a firm basis for the final selection, each proposer's plant was visited. Five contractors were selected, with deliveries scheduled for February through June 1976 (see Table 1-2 above). During the selection, strong emphasis was placed on previous experience and present manufacturing ability. The quantity to be procured from each contractor was negotiated with the contractor on the basis of price, schedule, and experience. The prices negotiated with each contractor were dependent upon the amount of testing, inspection, and documentation considered necessary as well as the basic manufacturing cost of the arrays. The average negotiated price is approximately \$21 per peak watt. The total procurement was increased to 46 kilowatts to allow for spares.

The initial modules have been fabricated and subjected to performance and environmental tests. Concern has arisen as to whether some of the early modules will be able to withstand the thermal cycle tests. The adequacy of the encapsulant materials to withstand the rigorous environmental conditions, the correctness of manufacturing techniques, the appropriateness of the test conditions, and the potential long range effects of these problems are being evaluated. Module deliveries have been postponed a few weeks until the above items are resolved.

When the decision was made to have an early 40-kilowatt procurement, it was also decided that an additional 130 kilowatts of solar arrays would be

purchased approximately a half year later. It was intended that these latter modules would incorporate selected design improvements to provide easier installation, less maintenance, and improved interchangeability in the field. The module design requirements and test conditions have been iterated with the ERDA Program Office, NASA/LeRC, and DOD numerous times. The desires and requirements of the array users (principally Lewis Research Center and the Department of Defense), in conjunction with laboratory and field test results plus design studies, have been incorporated into an RFP specification. The 130 kilowatt-procurement RFP was released to industry in December and includes a small business set-aside of 40 kilowatts. A broader segment of industry was solicited for this procurement than for the initial buy. Early in February 1976, 13 proposals were received with 6 reporting as small business. Proposal evaluation is proceeding on schedule. Deliveries are scheduled for late 1976 and early 1977.

Initial planning for a third buy — of 150 kilowatts — was started. The specifications for these modules will be formulated from the requirements and results gained by fabrication, test, and use of the prior procurements.

PART II

INTRODUCTION

A. BACKGROUND

Silicon solar cells have been successfully utilized for remote terrestrial electrical power applications for two decades. During this time, the cost per watt of solar cell arrays has been decreasing and the size of the commercial market has grown, although it is still minuscule relative to total electrical power generation. Prior to approximately 1972, terrestrial arrays were constructed utilizing solar cells that were rejects of the space program; however, the growth of the market prompted the innovation of solar array designs which were specifically oriented for the technical and economic requirements of a terrestrial applications market. A "price breakthrough" that is mainly attributed to the utilization of large-area round or wafer cells reduced the price from \$90 per peak watt to \$30 per peak watt. The round cells are produced with similar sunlight-to-electricity conversion efficiency but are produced more simply by requiring less processing per watt of power output. Though the change is modest, the cost is reduced dramatically. Additional dramatic price reductions are anticipated as a result of the ERDA Photovoltaic Conversion Program and LSSA Project activities.

Solar cell technology was initially developed at Bell Telephone Laboratories in the early 1950s. In 1955, the first field test was conducted in which telephone amplifiers were successfully powered by silicon solar cells. Experimental and special purpose terrestrial uses continued, but during the 1960s and early 1970s spacecraft electrical power systems were the major and only well-known application for this technology. The Vanguard I Satellite, launched in 1958, operated for six years; Pioneer VI has been operating in solar orbit since its 1965 launch. Various Mariner spacecraft have operated on solar power from the orbit of Mercury to beyond Mars. The largest solar photovoltaic system to date was that of Project Skylab, designed for 21-kilowatt capacity.

By the early 1970s photovoltaic theory had been developed, and the silicon solar-cell technology to support space applications and cost-limited special

terrestrial uses was well developed. However, the manufacturing of solar cells was relatively expensive. This severely limited widespread use, particularly where conventional electric-power sources were available. Solar cells made from other materials have been and continue to be investigated and developed in various laboratories. But the use of silicon for solar cells maintained a commanding lead over other materials because of proven reliability, the abundance of silicon, and an established although small silicon cell industry. Research and development activities were supported by NASA, the NSF, the Department of Defense, and various private institutions.

In 1971 the National Science Foundation's Research Applied to National Needs (RANN) program established an R&D program in terrestrial applications of solar energy. By mid-1973 NSF was sponsoring some forty projects, eleven of them in solar photovoltaics, and had collaborated with NASA in a major assessment and planning effort carried out by a jointly-supported Solar Energy Panel. This led to a major workshop on Photovoltaic Conversion of Solar Energy for Terrestrial Applications, held at Cherry Hill, N. J., in October 1973. This workshop consisted of six working groups concerned with the technology, panels concerned with the utilization of photovoltaic power systems, and the presentation of a group of invited papers. The working groups assessed the need for technology advances, the technical feasibility of achieving such advances, and research and development program considerations for single-crystal silicon cells, cadmium-sulfide copper-sulfide cells, polycrystal silicon cells, and alternative materials and devices. Other factors considered were the determination of terrestrial insolation, test and evaluation requirements, and the need for photovoltaic systems studies, tests, and design. The industry and utility panels considered many aspects of future terrestrial solar-photovoltaic applications, with emphasis on the need for a government-sponsored program of considerable duration.

A national photovoltaic plan was developed which considered inputs such as (1) the analysis of the conclusions and recommendations of the technical part of the Cherry Hill Workshop, (2) the photovoltaic conversion section in "The Nation's Energy Future", by Dr. D. L. Ray, and (3) a report of the Interagency Panel for Terrestrial applications of Solar Energy by a JPL team under NSF

sponsorship. This initial plan is contained in JPL Special Publication 43-11, "Assessment of the Technology Required to Develop Photovoltaic Power Systems for Large-Scale National Energy Applications", published October 15, 1974. The general 10-year goals of a solar array price less than 50 ¢ per peak watt and a production rate of 500 megawatts per year were formulated. In addition, activities required in the areas of technology development, photovoltaic power systems, and demonstration were outlined.

When ERDA was formed it acquired most of the responsibilities of the earlier NSF/RANN solar photovoltaic activity, including the foregoing plan. Thereafter, ERDA, in conjunction with other government agencies, industry, and potential users, reviewed, reevaluated, and extended the original plan during the formulation of the ERDA Photovoltaic Conversion Program. The Low-Cost Silicon Solar Array (LSSA) Project at JPL was initiated in January 1975 as a major element of the new Program. Its functional elements closely correspond to relevant elements of the new plan. In February 1975, a major Industry Briefing was conducted jointly in Washington, D. C., and Pasadena, California, to prepare for the initiation of a broad procurement program both for solar array technology development and for the continuing acquisition of state-of-the-art silicon solar arrays for various tests. In addition, analysis, study, and technical data activities were begun through the JPL Project Office which is responsible for management of the entire LSSA Project.

B. PROJECT MANAGEMENT

The Project is organized to support the ERDA Program - specifically, to meet the established objectives, and to provide for the organization, management, and integration of Project activities (Fig. 2-1). The management of the Project has been structured to implement the plans described in the Summary. The major functional activities for which the Project Manager is responsible are (1) technology development and transfer to commercialization, (2) procurement of state-of-the-art arrays, (3) analysis and integration of the Project, and (4) Project administration. These activities are directed toward development of the photovoltaic industry and stimulation of the market, with resulting price reductions.

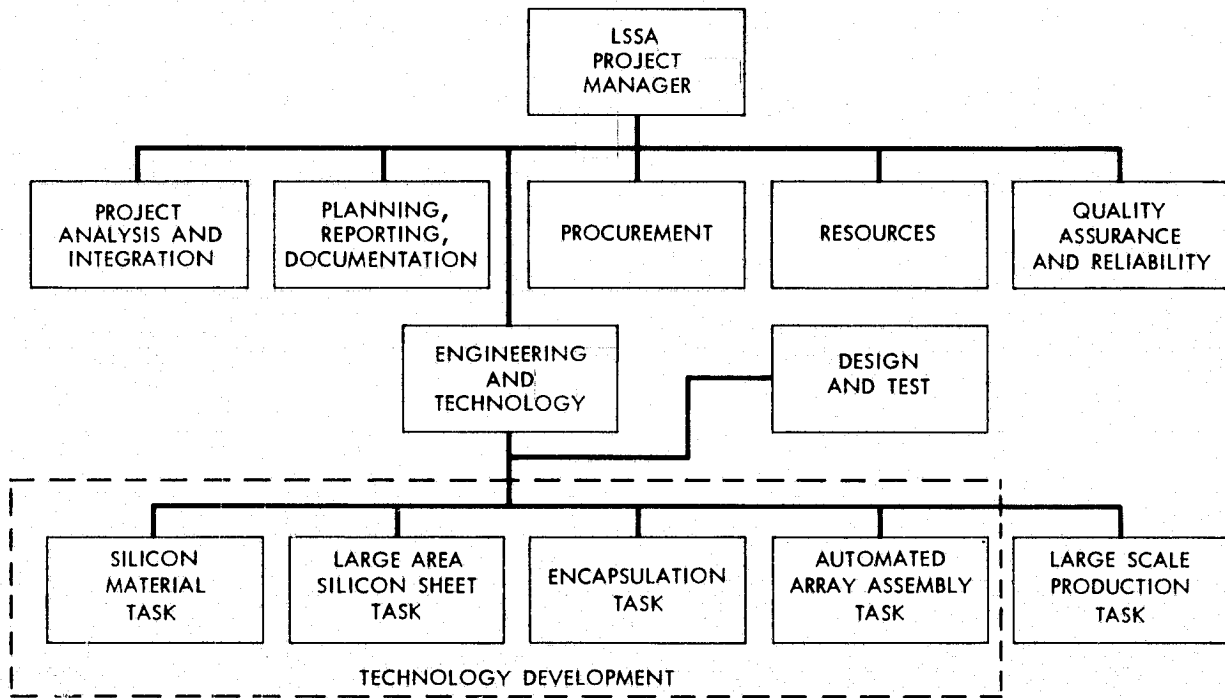


Fig. 2-1. Organization chart - Low-Cost Silicon Solar Array Project

The Project management has established a major effort for the interacting of technology development with the engineering for commercial production - the function of technology transfer. The Engineering and Technology Manager, who is responsible for both technology development and the procurement of arrays. He is supported by the Design and Test Engineer and backed by appropriate expertise necessary to perform this function. The technology development work has been divided into four key Tasks to provide for a more direct and efficient development effort to be conducted in these technology areas: silicon material, large sheet process, encapsulation, and automated manufacturing technology. The Large-Scale Production Task was established to provide for the annual procurements of the state-of-the-art hardware. Task Managers are assigned responsibility for their respective task areas and are provided technical and administrative support personnel including contract negotiators for their tasks

to maintain leadership and control over each contract and among the various contracts. Selected in-house effort is also administered by each Task Manager.

The design and test activity was established to (1) assist in the development of an integrated in-house test effort, (2) perform parametric engineering analysis and design of solar array modules for the development of more optimized hardware, (3) develop and define module design and test requirements, and coordinate activities between JPL and LeRC regarding module deliveries for the Test and Demonstration Project.

The Project Analysis and Integration (PA&I) Task supports the planning, integration and decision making activities of the Project. This support will be implemented by providing assessments of possible performance and economic consequences of alternative Project plans, developing the interface requirements among the Project tasks, supporting the establishment of the interface requirements between the LSSA Project and other ERDA Photovoltaic Conversion Program activities, and by developing the plans and procedures for integrating the tasks within the Project and between the Project activities and other elements of the Program.

The Quality Assurance and Reliability activity provides for the implementation of an effective quality program consistent with the Project overall objectives and provides the necessary inspection and support personnel for the various hardware procurements and related activities.

The Project Planning, Documentation and Data Management function provides the essential planning and documentation needed to administer and control Project activities. The acquisition, organization, and dissemination of technical information, a key function in technology transfer, is performed by the Project Data Center.

In the procurement activities, new, diversified and demanding requirements have been faced by the Project and ERDA. Therefore, experienced contract negotiators were assigned to the Project and a Procurement Manager designated to administer the Project's contracting activities in their initial phase of contractor selection and the later phase of contract management.

Project financial management is administered by a Resources Manager with supporting financial and contract analysts, making maximum use of the existing JPL financial reporting system.

The capability to assess the progress being made by the Project and the evolving solar array industry is under development for use in the continual adjustment of the Project's plans involving either or both management and technical activities, as required. This information will also be used to determine the requirements for experimental production plants and production plants as well as the Project general level of effort for continuing future activity. As the Project activities continue, contracts are expected to be added, modified, and some terminated to optimize the entire Project effort in accordance with the Program plans and objectives. JPL in-house effort will be applied in an adaptive mode to further adjust to the Program or Project needs, while maintaining a moderate in-house effort. This will permit necessary expertise to operate effectively in administering to the highly dynamic project, which seek innovative, productive ideas from industry, universities, and governmental agencies.

PART III

PROJECT ANALYSIS AND INTEGRATION TASK

The activities of the Project Analysis and Integration Task include the following:

- Assess the goals and progress of the LSSA Project.
- Contribute to the generation and development of Project plans.
- Establish standards for economic comparisons.
- Encourage effective communications and coordination.
- Develop necessary analytical capabilities.

The Project Analysis and Integration Task focuses on in-house activity, concentrating on promoting coordination among the technology development and array production tasks, analyzing potential Project plans and decisions, but also provides for the integration of the Project activities with the other elements of the ERDA Program.

During this initial year, the PA&I effort has contained the following four elements:

- Project assessment. A preliminary allocation of cost goals for each of the technology development tasks has been made, activity to define project assessment factors has been started, and a preliminary model to evaluate alternative array design costs has been developed; a procedure to estimate the cost of arrays resulting from defined manufacturing processes is now available.
- Fostering of communications and coordination both among the tasks within the Project and between the Project and other elements of the Program. The first LSSA Project Task Integration Meeting was held on January 12-14, 1976, involving contractors, JPL, and ERDA elements; significant interaction with ERDA headquarters, the Electric Power Research Institute (EPRI), and utility equipment

manufacturers took place with respect to development of the model for analyzing utility-owned solar electric power systems (USES).

- Development, adaptation, and implementation of techniques for analyzing the relevant technological and economic processes. A general model (USES) for estimating the "busbar" energy cost of alternative utility-owned solar electric power systems was developed jointly with ERDA and EPRI, and is being prepared for publication, and a simulation model of the solar array manufacturing industry (SAMIS) has been developed to estimate the costs of manufacturing.
- Consideration of barriers to commercialization. The existence of barriers to commercialization of photovoltaic power has been recognized, and efforts have been initiated to obtain an improved understanding of the barriers, with the objective of identifying, reducing, avoiding, or otherwise overcoming them.

A. PROJECT ASSESSMENT

1. Allocation of Cost Goals

In order to provide one of the bases for measuring the progress of the Project toward achieving its goals, a preliminary detailed allocation of cost goals for each of the major manufacturing steps for each year of the Project has been made. This allocation was strongly influenced by projections of the results of the technology development tasks now in progress. The detailed rationale is described below.

The general philosophy of the assumed cost reduction process is shown in Fig. 3 -1. Two major steps are anticipated, each followed by a period of more gradual subsequent price reduction. The first step is based on the assumption that the focused market provided by the ERDA Program procurements of solar arrays will promote some standardization and regularity in the industry. The second step is based on the assumption that the results of the technology development activities will be transferred to production practices.

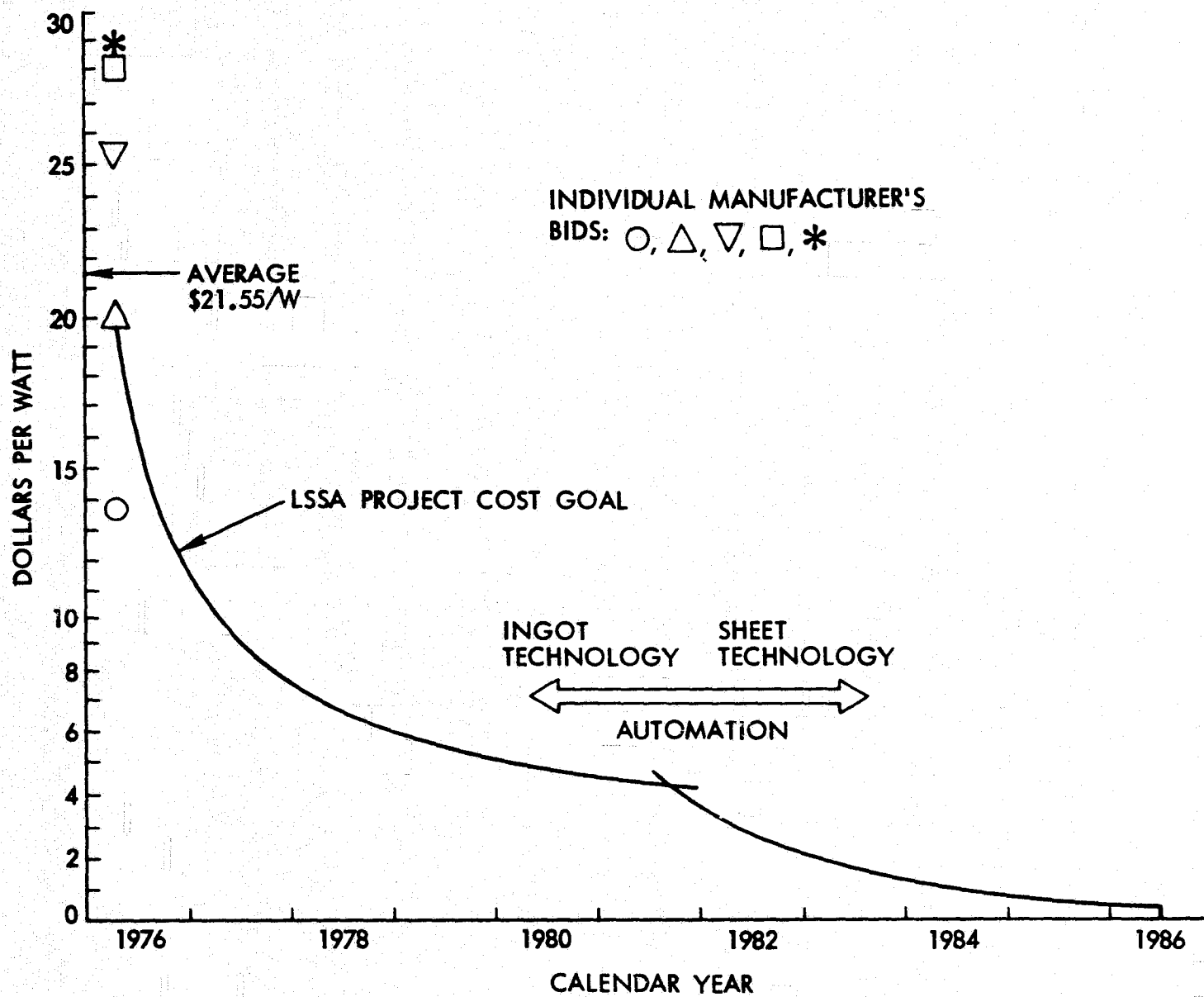


Fig. 3-1. Terrestrial solar array price history

The allocation of the cost goal trends is depicted in Fig. 3-2; the numerical details of these allocations are listed in Table 3-1. This allocation is intended to be preliminary and is expected to be refined (or possibly changed completely) as the results are iterated with the manufacturing industry and as the technology development tasks mature.

2. Definition of Project Assessment Factors

This effort is intended to support LSSA Project decision-making through evaluation, particularly by identifying the nature and importance of factors which may influence Project success. It is being carried out in three interacting areas: factor identification, development of a factor-processing methodology, and acquisition of practical experience through the solution of special trade-off problems which arise in Project operations. The approach is derived in part from aspects of flight-project mission analyses, and the goals and criteria are being iteratively redefined in this early stage of development.

A portion of a first-cut listing of candidate assessment factors, categorized by the segment of the Project to which they apply, is given in Table 3-2.

This listing is expected to be added to and edited by the operation of the factor-processing methodology, which includes extensive interaction with LSSA and ERDA as well as external information and judgement sources in various interview and critique processes. The processing methodology calls for four phased steps:

- 1) Determining which factors impact Project success, on the basis of Project goal association, positive or negative impact, and definition of success criteria; interacting with Project/Program elements to improve the first-cut list.
- 2) Evaluating factor impacts, developing and valuing a set of criteria, and weighting and ordering the factors, again with critical interaction.
- 3) Quantifying the impacts of the factors, with special methods for those factors on which evaluation consensus is not reached (in

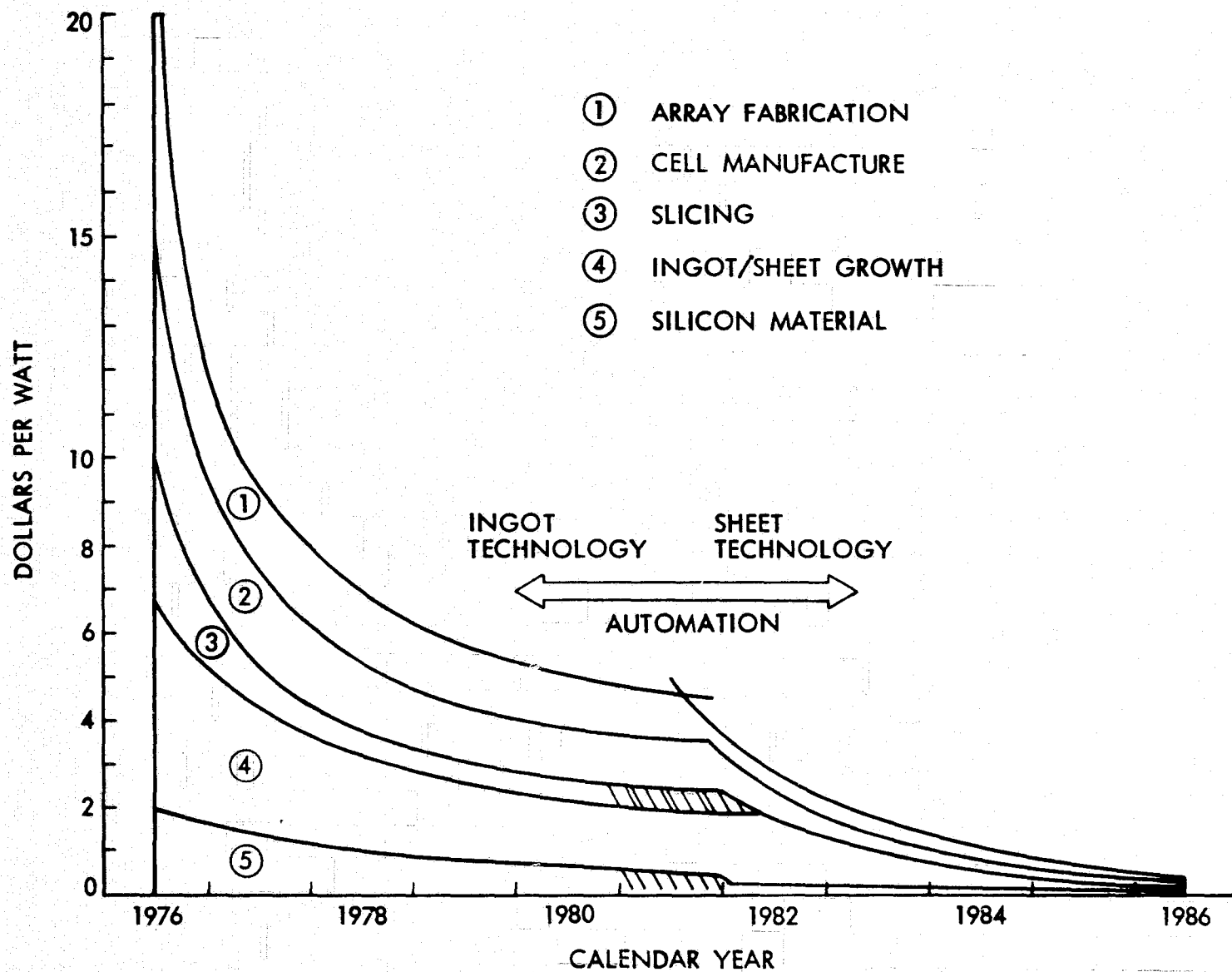


Fig. 3-2. Terrestrial solar array price goals

Table 3-1. Project cost goal allocations (all costs in 1975 dollars)

		CALENDAR YEAR					
		1976	1978	1980	1982	1984	1986
SILICON MATERIAL							
Silicon Material	Semiconductor Grade	Solar Grade					
	\$/kg	60	50	40	15	10	7
	\$/w	1.9	1.1	0.65	0.09	0.05	0.03
INGOT/SHEET GROWTH							
Processing Value Added - \$/w	Czochralski Ingots	Large Area Sheet					
		4.8	2.1	1.6	1.9	0.52	0.14
Wafer Material - \$/w		6.7	3.2	2.2	2.0	0.57	0.17
INGOT SLICING							
Processing Value Added - \$/w		3.7	0.6	0.5	0.01	0	0
Wafers - \$/w		10.4	3.8	2.7	2.0	0.57	0.17
CELL MANUFACTURE							
Materials Added (Contacts, etc.) - \$/w	Silver	Commercial Conductor					
		0.8	0.4	0.35	0.20	0.08	0.07
Processing Value Added - \$/w	Mostly Manual	Automated					
		4.3	1.2	0.85	0.25	0.09	0.06
Cells - \$/w		15.5	5.4	3.9	2.45	0.72	0.30
ARRAY FABRICATION							
Materials Added (Encapsulation, Framing, etc.) - \$/w		0.5	0.5	0.3	0.10	0.08	0.08
Processing Value Added - \$/w	Mostly Manual	Automated					
		4.0	1.1	0.8	0.45	0.18	0.12
ARRAY PRICE GOALS - \$/w		20	7	5	3	1	0.50
Silicon material in final product		27%	30%	38%	78%	87%	91%
Total processing value added		84%	71%	75%	87%	73%	64%
Watts/kg of silicon material		32	47	62	162	187	203
Cell efficiency (AM1)		11%	11.5%	12%	12.5%	13%	13.5%
Cell thickness - mils		15	12	12	10	10	10

Table 3-2. Candidate assessment factors

Project Segment			
Project Administration	Technical Development	Array Design and Testing	Commercialization...
Schedule	Array Cost	Reliability	Array Cost
Planning	Reliability	Maintainability	Performance
Manpower	Performance	Standardization	Standardization
Budget	Testing	Testing Load	Subsidies
Facilities	Environmental Impacts	Characteristics	User Acceptance
.	.	.	.
.	.	.	.
.	.	.	.

step 2 above); obtain expert-interview data as a structured parallel track relative to internal quantification (and evaluation and determination as appropriate).

- 4) Determining what actions must be taken to increase favorable impacts and reduce negative impacts; weighting actions relative to factors and using established factor quantifications and, as above, employing internal and external critical interactions.

The development of this methodology is expected to be influenced by the experience in developing and adjusting trade-off factors in studies carried out to support decisions on special problems which arise in various tasks of the LSSA Project. The first special-problem study has begun with respect to the question, in the LSSA Large-Scale Production Task, of whether and/or how much of the future 150-kilowatt procurement should be held at the technology level of the 130-kilowatt procurement in order to create an appropriate time interval for adequate evaluation, analysis, and feedback from both the previous 46-kilowatt procurement and the design activity of the 130-kilowatt buy.

3. Evaluation of Alternative Design Concepts

A Project Alternative Design Evaluation Model (PADEM) to compare the overall performance of alternative silicon solar array designs is being developed.

Owing to the wide variety of solar power applications, types of electrical loads, and operating environments, a single normative performance index value does not appear to be suitable. Rather, there must be many such values, tailored to different applications, loads, and environments.

Study of a number of criteria by which the performance of an array design can be evaluated has led to the conclusion that the performance index can be adequately characterized by three summary components: total cost, electrical performance, and convenience. The total cost includes acquisition and installation costs, operating and maintenance costs, and the time value of money. A procedure for expressing total cost on an annualized basis has been developed. The electrical performance calculation is complicated by the likelihood that the performance of each array design may vary differently according to varying environmental factors. The mode of predicting such performance variations and their integration has not been defined further than the requirements for testing each module design under broadly differing conditions. It has been established, however, that the appropriate measure of electrical performance is the total (or average) energy produced over the course of a year in the specified application.

Convenience factors are associated principally with specific system applications, e. g., lightweight for portable uses. Many of these factors are not easily measurable and a few may be difficult even to design. In no case are they capable of normalization so that designs might be compared on this basis without specifying the application. Analysis of this set of factors, preliminary as yet, suggests that while, in general, evaluation and selection from among alternative designs of a "standard" configuration is possible on the basis of performance/cost criteria, selection of nonstandard designs for convenience will keep such designs in the market for special applications.

4. Estimation of the Impact of Research Efforts on Array Costs

Through use of the Solar Array Manufacturing Industry Simulation (SAMIS) model, which will be described in detail below, the maximum impact on the cost of manufacturing solar arrays that can result from any of the technology development tasks can be estimated. It is expected that this capability will be usable in the allocation of LSSA Project resources.

B. PROJECT INTEGRATION

The first Project/Task Integration Meeting was conducted in mid-January 1976 (the Proceedings were published early in March). The focus of this meeting was Project and task planning and status, together with intra-task interface matters. The focus established for the second Project Integration Meeting, scheduled for late April, also included inter-task interfaces and integration work, as well as interfaces with other elements of the Photovoltaic Program.

The LSSA Project interfaces with the ERDA Program Office, the System Definition Project, the Test and Demonstration Project, and the Mission Analysis studies were examined and laid out in preliminary fashion, and then were iterated through integration planning meetings conducted with Sandia Laboratories (Systems Definition), NASA Lewis Research Center, Department of Defense MERADCOM (Test and Demonstration), and Aerospace Corporation (Mission Analysis). These iterations continue through ad hoc meetings and through the ERDA Program Office's quarterly review/interface meetings.

C. DEVELOPMENT OF ANALYTIC TECHNIQUES

1. Utility-Owned Solar Electric System (USES) Model

This economic evaluation model is designed to operate on cost figures resulting from the acquisition, installation, and maintenance of a solar energy system (not limited to photovoltaics) by a public or private utility, and to derive the energy "price" necessary to recover those costs, assuming scale and load

factors. It has been developed jointly with ERDA and the Electric Power Research Institute to provide energy analysts a simple, convenient, and standard tool for ranking candidate systems in order of cost-effectiveness. Documentation of the model is in preparation.

The model is designed to accommodate energy systems with different technical and economic features, but not to be so sensitive to system-specific details as to preclude planning-level evaluation and comparisons. It is compatible with conventional business practices for cost projection and capital budgeting.

The basic structure of the model is given in the flow diagram of Fig. 3-3. The following discussion summarizes the sequence of calculations. The cost of capital to the utility and its annualized fixed charge rate are computed from these equations, where the symbols are defined in Fig. 3-3:

$$k = (1 - \tau)k_d \frac{D}{V} + k_c \frac{C}{V} + k_p \frac{P}{V}$$

$$\overline{FCR} = \frac{1}{1 - \tau} \left(CRF_{k, N} - \frac{\tau}{N} \right) + \beta_1 + \beta_2$$

The present values of the initial and recurrent cash flows are obtained from

$$CI_{pv} = (1 + g)^d \sum_t \left[CI_t \left(\frac{1 + g}{1 + k} \right)^j \right]$$

$$X_{pv} = \begin{cases} (1 + g)^d X_0 & \frac{1 + g}{k - g} \left[1 - \left(\frac{1 + g}{1 + k} \right)^N \right] & \text{if } k \neq g \\ N \cdot X_0 & \text{if } k = g \end{cases}$$

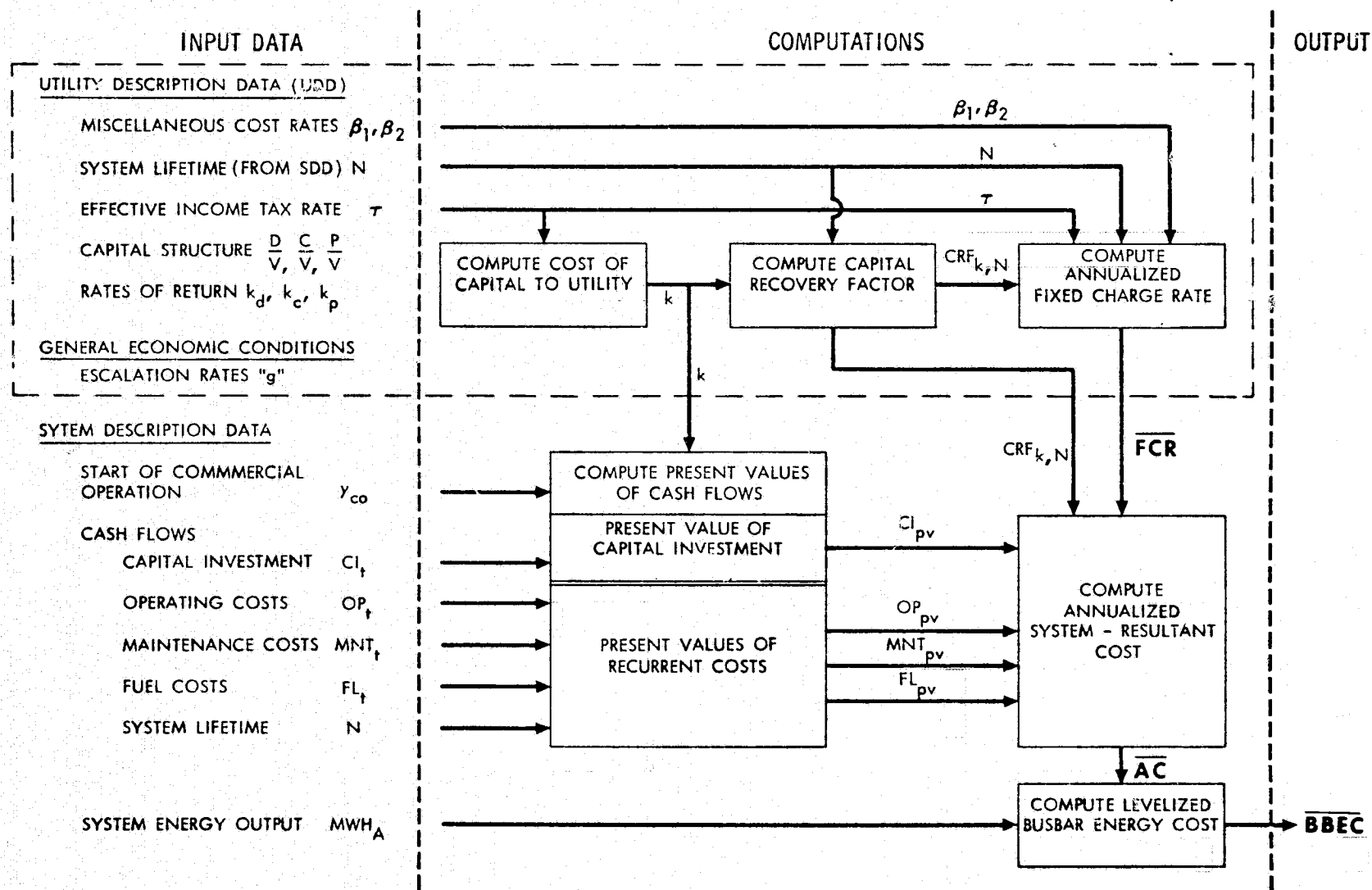


Fig. 3-3. Structure of USES model

where X is replaced by OP, MNT, or FL, as appropriate; d = number of years from price information to start of commercial operation; and j = number of years from start of commercial operation to the occurrence of capital investment.

The annualized cost is obtained from

$$\overline{AC} = \overline{FCR} \cdot CI_{pv} + CRF_{k, N} \cdot OP_{pv} + MNT_{pv} + FL_{pv}$$

and is then divided by the system's energy output to produce an estimate of the levelized busbar energy cost:

$$\overline{BBEC} = \frac{\overline{AC}}{MWH_A}$$

This levelized charge, which produces adequate revenue to recover system costs, is a single number summarizing the likely distribution of real and different rates, as represented in Fig. 3-4. It covers interest and profit, as the flow diagram shows.

The interactions of a solar-energy system with other supply systems and the constituency of users across the whole utility are not taken up by this model. Thus only if the effects on the utility are comparable can comparison between two different systems using this model be considered entirely valid.

2. Solar Array Manufacturing Industry Simulation (SAMIS) Model

The purpose of SAMIS is to provide an understanding of the potential benefits of scientific research into the materials and processes involved in the manufacture of arrays for the photovoltaic conversion of solar energy. The procedure which is being developed for this purpose also allows study of the effects of various fiscal policies of manufacturers and of possible governmental actions.

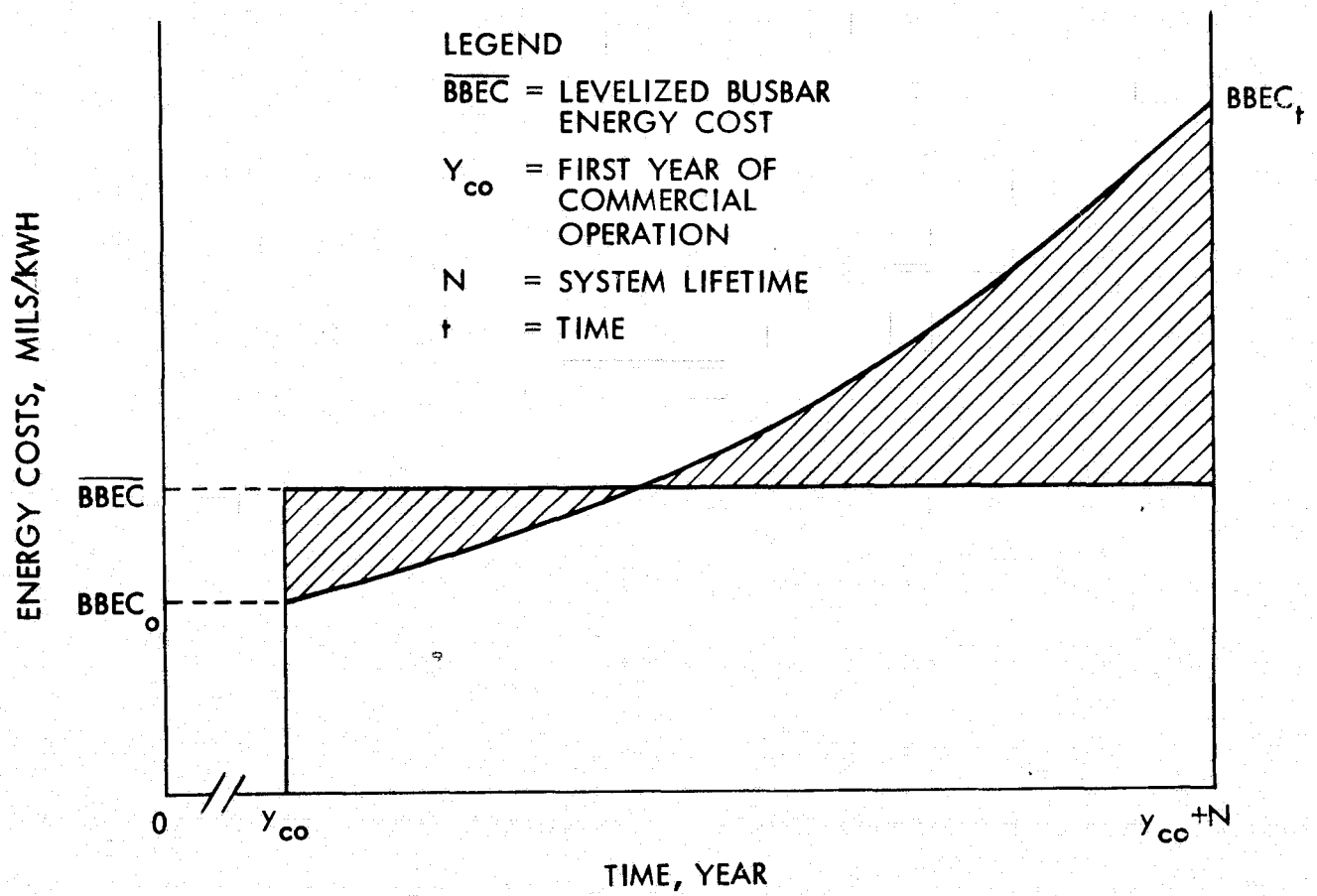


Fig. 3-4. Comparison of levelized energy cost with growing energy costs

To accomplish its purpose, SAMIS is a three-part effort. The first is the construction of a computer program that will understand a description of the structure of a manufacturing industry, then simulate the response of that industry to an order for a specified quantity of its end product. The second part of the SAMIS effort is the description of the industry structures that would result from the use of particular technological processes for the manufacture of photovoltaic solar arrays. The third part is the use of the SAMIS computer program to investigate the sensitivity of the price of solar photovoltaic power capability (and, perhaps, the values of other quantities of interest, such as the energy payback time) to variations in the technological processes and in the values of parameters that describe industrial policies, governmental actions, and/or the costs of required goods and services.

The SAMIS Computer Program assumes that the industry can be represented as a collection of single-product manufacturing firms. The end product of the industry (that is, annual newly-installed solar photovoltaic power production capability) is assumed to be produced by a manufacturer who requires certain other products and services as input. SAMIS assumes that each of these other products and services is produced by another manufacturer. Each of these manufacturing firms requires additional products and services, and so on. Eventually, products or raw materials are identified for which the market simply supplies a price. The industry description must supply SAMIS with how much of each required product and service is needed as a function of how much of each requiring product is to be produced.

Since it is being assumed that a particular set of technological processes is being used, SAMIS does not need to know the prices of the intermediate products when it is calculating the quantities. This is a necessary assumption, because at this point not all of the prices are known. After following the trail of orders to its ends, SAMIS's next step is to go back "up" the structure, computing prices.

The price of each firm's product can be computed by constructing a mathematical model of the firm's finances. Such a model can be obtained by setting the firm's total income equal to its total outgo (which must include

earnings and investment), replacing terms in that equation by successive submodels which contain parameters (such as total capital required, legal minimum lifetime for depreciation of equipment, and the required return on equity) that will be used to describe the firm, and solving for the unit price of the product.

This procedure causes some of the variables that are results in the real world, such as earnings, to become inputs to the model. It is this inversion of the roles of such variables that makes it necessary to caution the user of SAMIS. In the real world, the firm sets the price of its product, the amount of sales effort, and a host of other factors, and accepts whatever profit (or loss) results. In SAMIS, the user specifies the profit, the interest rate for corporate bonds, the ratio of debt to equity, and other parameters; SAMIS then calculates the quantity of product sold from the industry description supplied by the user, and the product price. The "supply price" estimated by SAMIS is that price at which the manufacturer would just meet all of his financial obligations, including profit, taxes, replacement of capital goods, and so on, assuming that the quantity sold is that which is implied by the industry description.

For realism in describing the industry, the submodels contained within SAMIS allow a considerable amount of flexibility. For example, the following parameters may be defined as functions of quantity: the unit prices of purchased goods and services, the capital required by each manufacturing plant, and the relative amounts of required goods and services. In addition, each manufacturing firm may have different values for the parameters that describe its financial characteristics.

SAMIS price estimates depend upon a lot of user-supplied data, much of which cannot be known precisely. To increase the usefulness of its results, SAMIS provides for consideration of uncertainties in the data by requiring the user to state minimum, median, and maximum values for all parameters and then computing a (specifiable) number of Monte Carlo estimates. Means, standard deviations, and histograms of the prices and quantities can be displayed. (If but a single trial is specified, median values are used throughout the computation.)

A typical SAMIS industry description is illustrated in Fig. 3-5. Figure 3-5 does not show the values of the financial parameters of the firms, which are also part of the industry description input. This description uses processes which are consistent with the current state of the art, but no current manufacturer does things in exactly the assumed fashion. Some additional modeling, external to the SAMIS computer program, is required to produce the parameters shown. For example the figure of 1.32 wafers/cell takes into account breakage, metalization failure, and so on.

Additional industry descriptions will be developed to describe the structures that would result from the use of other technological processes, such as those that use monocrystal silicon ribbons or sheets.

D. COMMERCIALIZATION

The modularity of Solar Photovoltaic Conversion Systems (SPCS) makes it possible for these systems to have applications ranging from small remote or portable power systems, individual residential or commercial power systems, to large central power plants. Consequently, the potential users of SPCS are not necessarily restricted to private or public power utilities, but easily include governmental agencies such as the U. S. Forest Service, the U. S. Coast Guard, federal/state/local law enforcement agencies, water districts, etc.; private organizations such as the building and construction industry, industrial parks, commercial shopping centers, recreational facilities, etc.; and individual building or home owners.

The wide range of possible users creates an especially difficult marketing problem for the solar array manufacturers if these users represent the purchasers of solar arrays, or even if these users represent a market for a number of power system application suppliers who, in turn, are the purchasers of solar arrays. In either case, the solar array supplier industry is, in all likelihood, looking at a relatively unknown and possibly quite dispersed market. The ERDA Photovoltaic Conversion Program is seeking to identify the potential market by conducting various mission and system studies; it will begin to aggregate some

ANNUAL NEW PHOTOVOLTAIC POWER CAPABILITY
PEAK WATTS PER YEAR

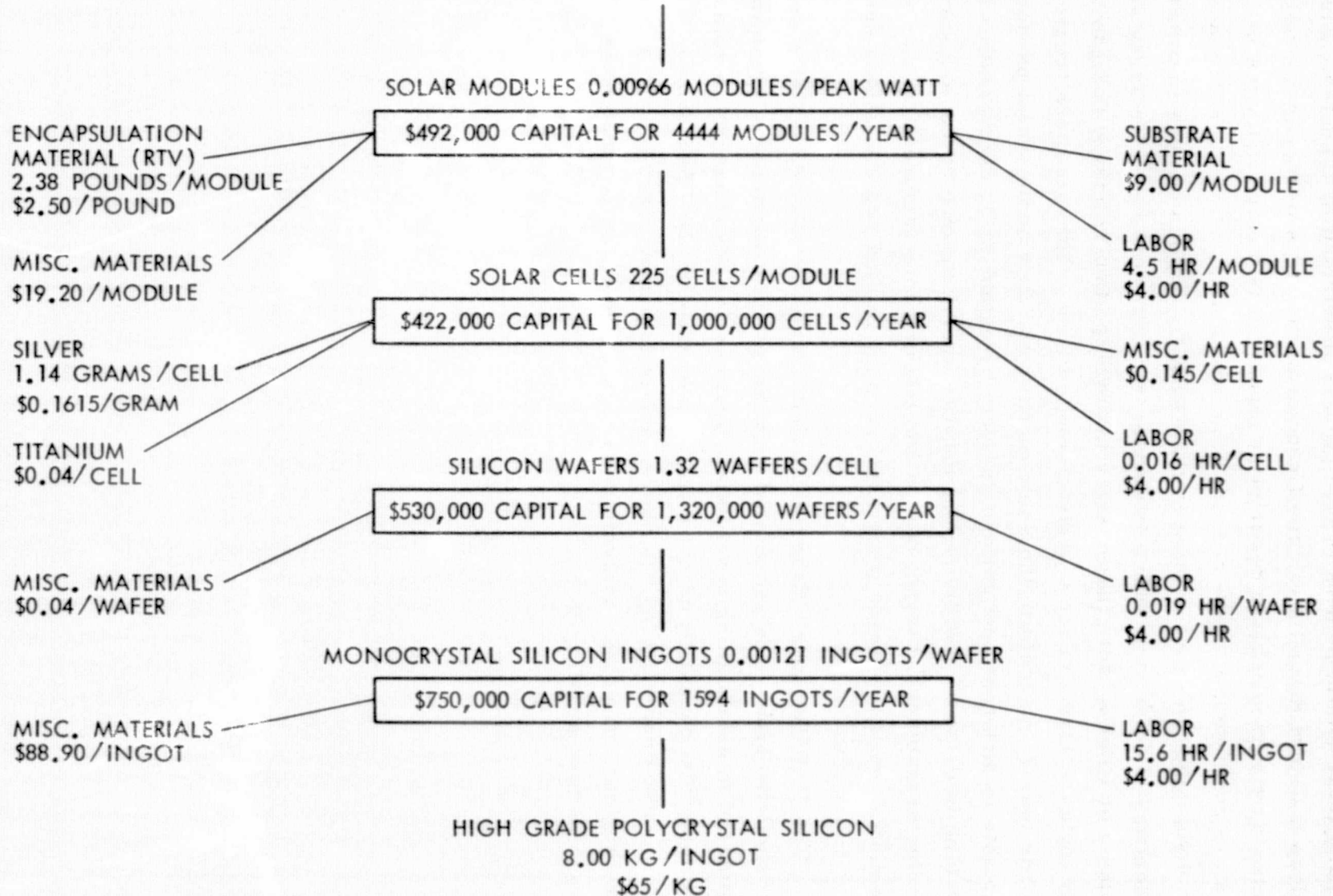


Fig. 3-5. A SAMIS description of an industry based on Czochralski ingots

of the market by cooperative programs with governmental agencies such as the Department of Defense, U. S. Forest Service, U. S. Coast Guard, and with the Electrical Power Research Institute of the utility industry.

The LSSA Project element of the ERDA Program will seek to minimize the difficulties of commercialization in a diverse market for the solar array supplier industry by working with the industry to develop standard array designs to cover as many as possible of the variety of applications. This approach treats the diverse market problem in the same manner as other commercial products adaptable to different applications, namely by establishing configuration limits, matching interfaces, and interchangeability specifications, while accommodating manufacturer-unique internal design and performance features. It also will give consideration to areas where special applications require unique designs.

The PADEM model, described briefly in III-A-3 above, is being developed to analyze the trade-offs associated with the various parameters which must be considered in establishing design specifications for interchangeable solar arrays. This analytical capability is expected to interact with the USES and SAMIS models, also described briefly above, and to interface directly with a solar array engineering design analysis capability being developed under the LSSA design and test activity.

PART IV
TECHNOLOGY DEVELOPMENT TASKS

TASK 1. SILICON MATERIAL

The objective of the Silicon Material Task is to establish, by 1984, an installed plant capability for producing silicon suitable for solar cells at a rate equivalent to 500 MW (peak) of solar arrays per year at a price of less than \$10 per kilogram. The program formulated to achieve this objective is based on the conclusion that the price goal can not be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade silicon. Consequently, it is necessary that either a different process be developed for producing semiconductor-grade silicon or a less pure and less costly silicon material (i.e., a solar-cell-grade silicon) be shown to be utilizable.

A. TECHNICAL BACKGROUND

Solar cells are presently fabricated from semiconductor-grade silicon, which has a market price of about \$65 per kilogram. A drastic price reduction of material is necessary to meet the economic objectives of the LSSA Project. One means for meeting this requirement is to devise a process for producing a silicon material which is significantly less pure than semiconductor-grade silicon; the price goal for this material is less than \$10 per kilogram. However, the allowance for the cost of silicon material in the overall economics of the solar arrays for LSSA is dependent on optimization trade-offs, which concomitantly treat the effects of the price of silicon material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide the information for the optimization trade-offs and to develop processes for producing different impurity-grades of silicon at high volume and low cost.

B. ORGANIZATION OF THE TASK I EFFORT

The Task I effort is organized into five phases. As Table 4-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade silicon will be demonstrated. In Part II the effects of impurities on the properties of single crystal silicon material and the performance characteristics of solar cells, as well as the consequences of various processing procedures, will be investigated. This body of information will serve as a guide in developing processes (in Part III) for the production of solar-cell-grade silicon. The process developments in Parts I and III will be accomplished through chemical-reaction, chemical-engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various silicon-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies and the most promising processes will have been selected.

Phase II will be initiated to obtain scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of a large-scale production plant.

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, experimental plants will be used to obtain technical and economic evidence of large-scale production potential. In the experimental plant phase (i. e., Phase III) there will be opportunities to correct design errors; to determine energy consumption; to establish practical operating procedures and production conditions; and to more realistically evaluate the requirements for instrumentation, controls, and on-line analyses.

Table 4-1. Organization of the Task 1 effort

	Objective
Phase I	Demonstrate the technical feasibility and practicality of processes for producing silicon.
Part I	Establish the practicality of a process capable of high volume production of semiconductor-grade silicon at a markedly reduced cost.
Part II	Investigate the effects of impurities on the properties of single crystal silicon material and the performance characteristics of solar cells as well as the consequences of various processing procedures.
Part III	Establish the practicality of a process capable of high volume production of solar-cell-grade silicon at a price of less than \$10 per kilogram.
Part IV	Evaluate the relative commercial potentials of the silicon-production processes developed under Phase I.
Phase II	Obtain process scale-up information.
Phase III	Conduct experimental plant operations to obtain technical and economic evidence of large-scale production potential.
Phase IV	Design, install, and operate a full-scale commercial plant capable of meeting the production objective.

In the final phase of Task 1 (i. e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The experimental plant and the commercial plant will be operated concurrently so as to permit the use of the experimental plant for investigations of plant operations, i. e., for problem solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of Task 1 will be conducted in supporting efforts. These supporting subtasks will be accomplished under contract and by an in-house JPL program.

C. TASK 1 CONTRACTS

Proposals for appropriate programs to implement Phase I of Task 1 were solicited by means of Requests for Proposals (RFPs). In addition, unsolicited proposals have been and are continuing to be received. All proposals are given careful evaluation.

The team which evaluated the proposals submitted in response to the silicon material RFP recommended that seven contracts be negotiated: three for Part I, two for Part II, and two for Part III. The contractors selected are shown in Table 4-2. Only the Dow Corning contract remains to be negotiated. As the table indicates, unsolicited proposals have thus far resulted in a contract award to Lamar University and three potential awards.

D. TASK 1 TECHNICAL ACTIVITY

The objectives of Phase I of Task 1 are as follows: Part I - Establish the practicality of a process capable of the high volume production of semiconductor-grade silicon at a markedly reduced cost; Part II - Investigate the effects of impurities on the properties of single crystal silicon material and the performance characteristics of solar cells as well as the consequences of various processing procedures; and Part III - Establish the practicality of a process capable of the high volume production of solar-cell-grade silicon at price less than \$10 per kilogram; and Part IV - Evaluate the relative commercial practicality of the silicon-production processes developed under Phase I of Task 1.

1. Processes for Producing Semiconductor-Grade Silicon

The approach used for Part I incorporates theoretical studies involving thermodynamics, reaction chemistry, and chemical engineering; chemical reaction investigations consisting of the experimental determinations of reaction kinetics, yields, and suitable process conditions; a chemical engineering effort for securing an experimental data base for preliminary process modeling; and energy-use and economic calculations for preliminary process models. In each

Table 4-2. Task 1 contractors

Note: All Task 1 contracts, current or proposed, are for work under Phase I

Contractor	Technology Area
SEMICONDUCTOR-GRADE PRODUCTION PROCESSES (Part I of Phase I)	
Battelle Memorial Institute, Columbus, Ohio	Si from SiCl_4 or SiI_4
Motorola, Phoenix, Arizona	Si using SiF_4 transfer
Union Carbide, Sistersville, W. Virginia	Si from SiH_4
SOLAR-CELL-GRADE SPECIFICATIONS (Part II of Phase I)	
Monsanto Research, St. Louis, Missouri	Investigation of effects of impurities on solar cell performance
Westinghouse Electric, Pittsburgh, Pennsylvania	Investigation of effects of impurities on solar cell performance
SOLAR-CELL-GRADE PRODUCTION PROCESSES (Part III of Phase I)	
Dow Corning, ¹ Hemlock, Michigan	Si from pure source materials using arc furnace processing
Texas Instruments, Dallas, Texas	Si from C reduction of SiO_2 using plasma processing
Stanford Research Institute Menlo Park, California	Si by duplex vapor-electrochemical conversion of SiF_4
Westinghouse Electric ^{1, 2} Pittsburgh, Pennsylvania	Si by plasma-arc-heater reduction of SiCl_4 with H_2 and alkali metals as reducing agents
AeroChem Research Labora- tories ^{1, 2} , Princeton, New Jersey	Si by use of a non-equilibrium plasma jet
COMMERCIAL POTENTIAL OF PROCESSES (Part IV of Phase I)	
Lamar University, ² Beaumont, Texas	Evaluate relative commercial potentials of Si-production processes developed under Task 1
¹ Contract to be awarded in Spring of 1976. ² Unsolicited proposal.	

case the contract requires a demonstration of technical feasibility and a projection of commercial practicality, involving the preliminary analysis of suitability for a scale-up study. The evaluation of each process as a candidate for the Phase II scale-up studies is scheduled for early 1977.

- a. Semiconductor-Grade Si Production by (a) Zn Reduction of SiCl_4 , (b) Reduction of SiI_4 with H_2 and (c) Thermal Decomposition of SiI_4 - Battelle Memorial Institute

The objective of the program at the Battelle Memorial Institute is to determine the practicality of utilizing the Zn^* reduction of SiCl_4 or the thermal dissociation, or reduction by H_2 , of SiI_4 to meet the goal of Part I. Practicality will be demonstrated by the operation of a small processing unit. Selection of the process to be used for the unit will be based on the results of analyses and comparisons of the technology, economics, and energy use of the process-candidates.

The first work under this contract included calculations of equilibrium yields for assumed practical operating conditions, formulation of preliminary process flow sheets, calculations of mass and energy balances, and experimental investigations of options for the two processes.

For the literature search, the reactions to be studied were used as guidelines: the Zn reduction of SiCl_4 , the thermal decomposition of SiI_4 , the H_2 reduction of SiI_4 , the electrolysis of ZnCl_2 , the formation of SiI_4 by reacting I_2 with metallurgical grade Si or with a mixture of SiO_2 and C, and I_2 recovery processes. The characteristics to be included in the investigation were thermodynamic properties, reaction kinetics, process technology and costs, materials of construction, energy-use, chemical analyses, and the effects of Zn as an impurity in Si.

* Zinc. For identification of chemical symbols, see List of Abbreviations.

Zn Reduction of SiCl_4 : The preliminary process-flow diagram for the Zn reduction of SiCl_4 (Fig. 4-1) was devised to illustrate some of the options and operating conditions which need to be considered. This process incorporates sections for investigations of (1) Zn and SiCl_4 , which react in the fluidized bed deposition at about 900°C , (2) the recovery of ZnCl_2 and the subsequent regeneration of Zn by electrolysis, and (3) the recovery and purification by distillation of SiCl_4 . Alternative steps of the process will be introduced and assessed when necessary.

Thermodynamic calculations were made to examine equilibrium yields for several conditions and to provide a basis for the subsequent energy balance determination. At the start a difference between the free energies of formation of ZnCl_2 as calculated from the entropy, enthalpy, and heat capacity data and from the fused salt emf data was found. This was resolved by substituting another set of experimental data for the melting point and the heat and entropy of fusion. Using these data, values for $-\Delta G^\circ_f$ were calculated for the temperature range of 300° to 1500°K . These values were then used in the calculations of the equilibrium conversion efficiency values of the reduction reaction. The results are shown in Fig. 4-2, which also illustrates the effect of a diluent gas. The operating temperature, based on these data, is likely to be between the dew point of ZnCl_2 at 1005°K and 1300°K . The final determination will result primarily from considerations of the experimental rate and yield data.

Experiments involving the introduction of Zn as a solid, which is passed through a high temperature zone prior to reaction with SiCl_4 in a fluidized bed, have failed to yield deposition of Si in the bed. The reaction invariably occurs above the bed and results in a blockage of the preheated zone. As a consequence, this mode has been eliminated from further consideration.

The experiments in which Zn was introduced as a vapor were performed in an apparatus shown in Fig. 4-3, which utilizes a fluidized bed deposition reactor. The results indicate that fluidization can be achieved, that the process will provide a relatively high conversion efficiency of at least 45% at

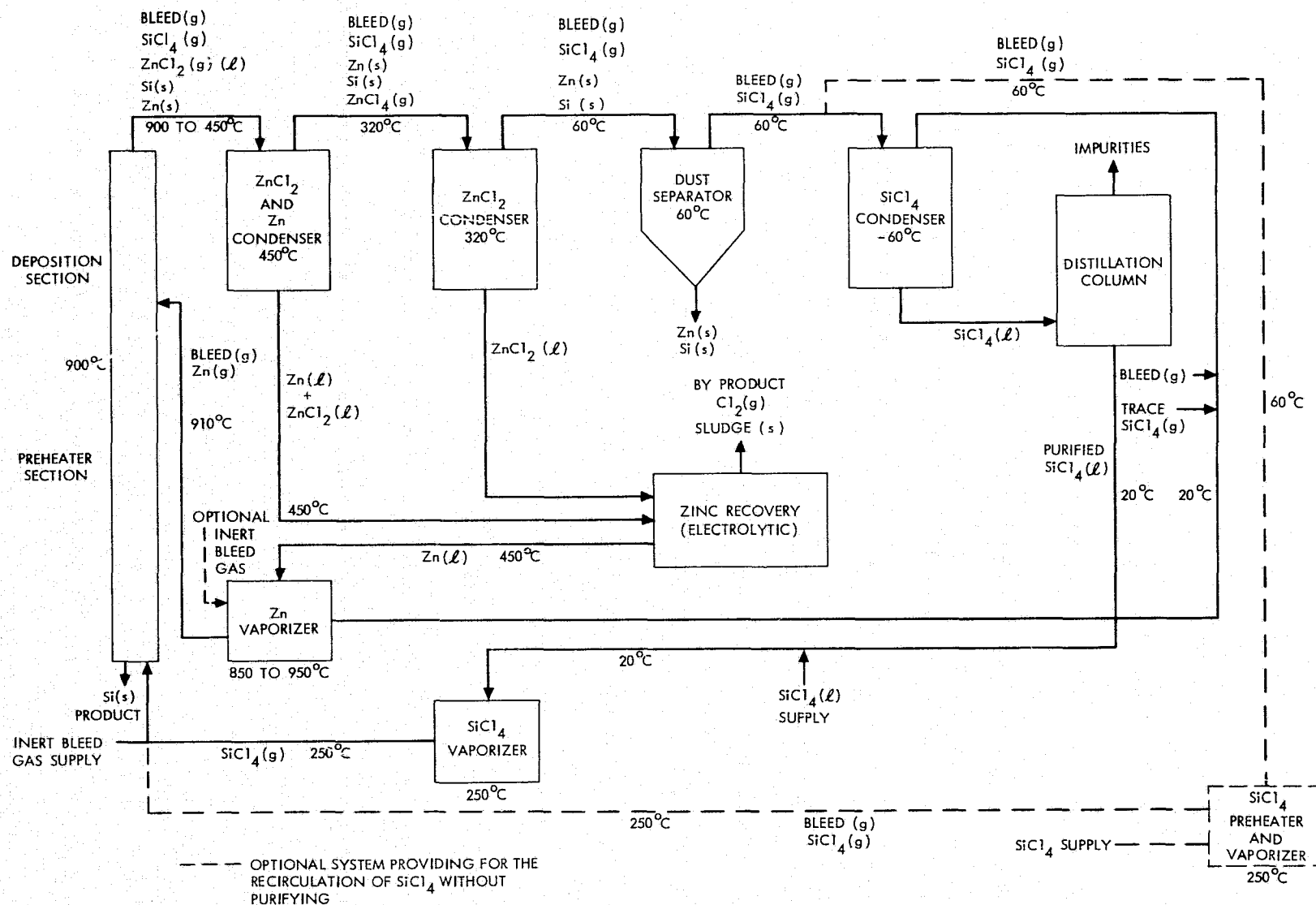


Fig. 4-1. Preliminary flow diagram for the preparation of Si by Zn reduction of SiCl_4

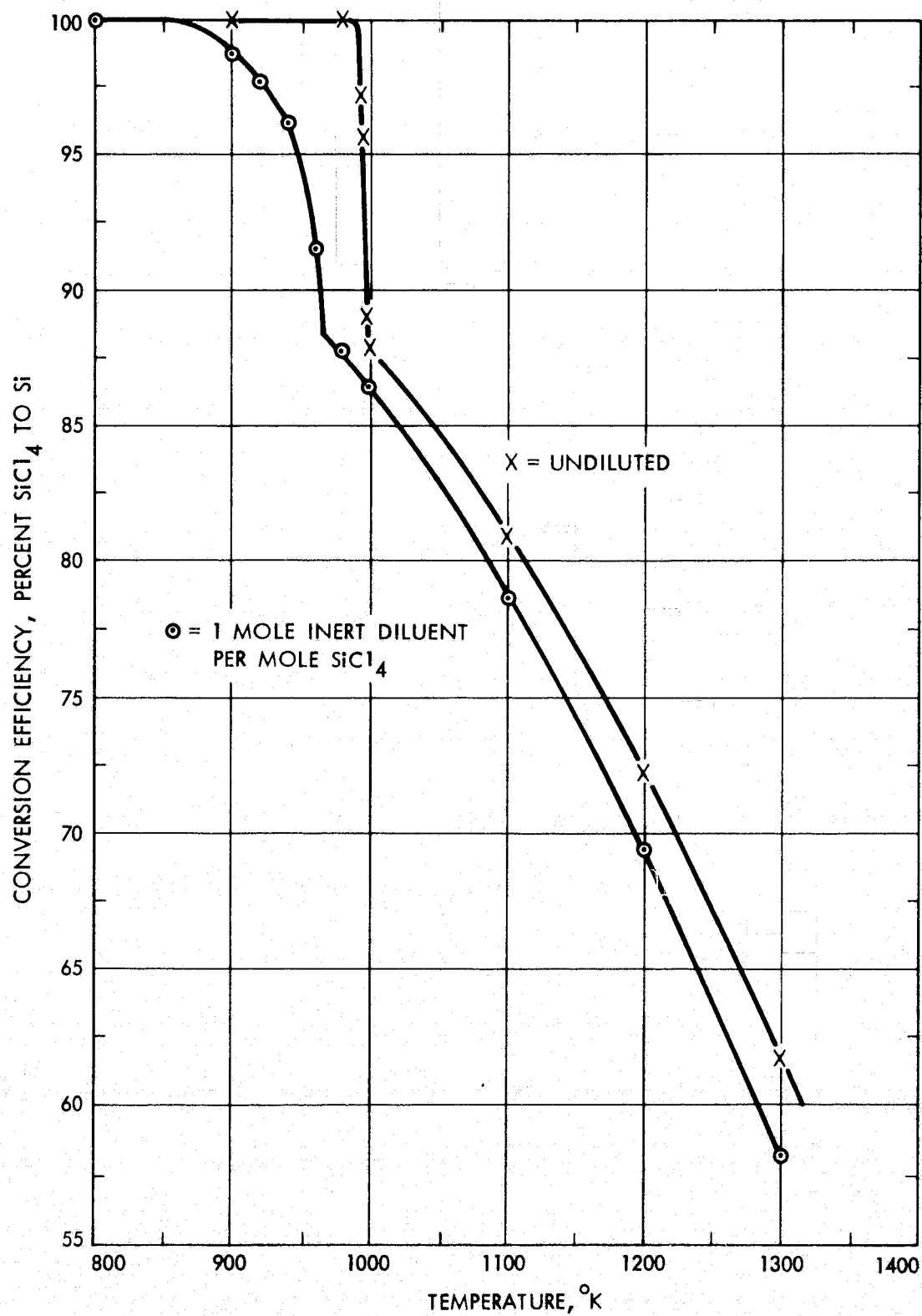


Fig. 4-2. Conversion efficiency, $2 \text{ Zn} + \text{SiCl}_4 = 2 \text{ ZnCl}_2 + \text{Si}$

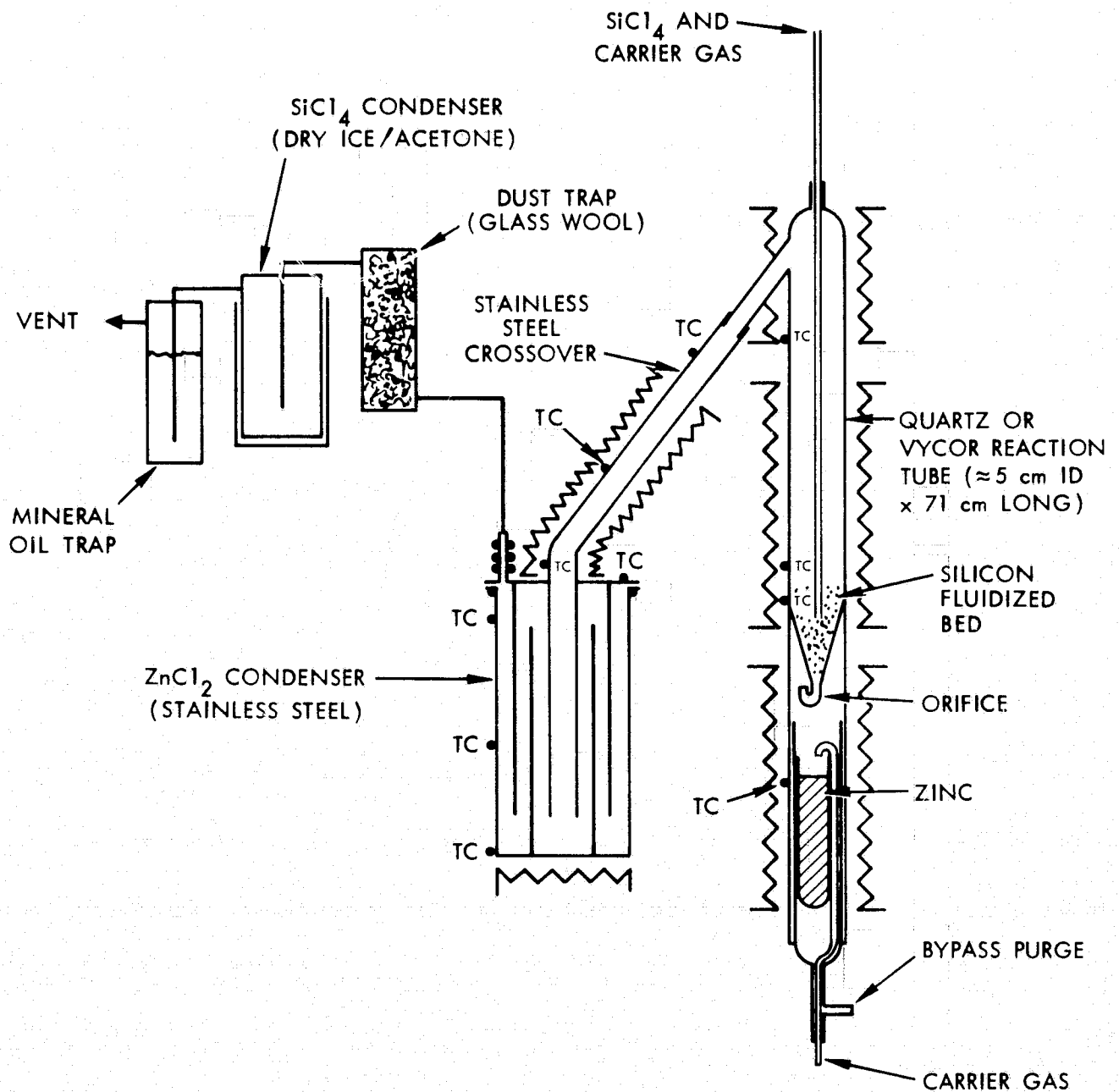


Fig. 4-3. Schematic of unit for the preparation of Si by the Zn (vapor feed) reduction of SiCl₄

deposition temperatures less than 1000°C , and that the Zn/ZnCl_2 condensate can be handled at 500°C . The electrolytic recovery of Zn from ZnCl_2 has been proven to be commercially practical, with 89% electrochemical efficiency using 4.53 kilowatt-hours per kilogram of Si.

Preliminary calculations of the energy and mass balances have been made using a simplified flow chart, shown in Fig. 4-4. For the condition that no sensible heat is recovered, the total energy requirements were determined to be about 14.8 kilowatt-hours per kilogram of Si produced; if all of the heat is recovered, the value becomes about 7 kilowatt-hours per kilogram.

The theoretical and experimental results to date have indicated no technical block to the Zn vapor - SiCl_4 process. A much more complete examination of the deposition step in the fluidized bed is in progress. The parameters of temperature, stoichiometry, gas flows, reactor design, and process assembly will be used to study the process characteristics of rate, yield, and energy use. The mass and energy-use balances will be periodically iterated. The product of the next phase of this work will be a much better understanding of the operating characteristics, economics, and energy use of the process.

Decomposition and Reduction of SiI_4 : The results of preliminary consideration of the options and operating conditions for a process for the decomposition and reduction of SiI_4 (which includes the iodination of a SiO_2/C mixture to form SiI_4 and subsequent reduction by H_2 of the SiI_4) are shown in Fig. 4-5. The reactions contained in this flow diagram are the iodination; the recycling step for the I_2 ; the purification of the SiI_4 by distillation; the Si deposition at greater than 1000°C ; and the recovery of the by-products, I_2 and HI , and of the unreacted SiI_4 and H_2 . The options for the deposition step are hot wire, hot wall, and fluidized bed; the fluidized bed operation will require the least energy input and is predicted to have the best efficiency. This process will be assessed section by section, and alternative steps will be introduced as required.

Thermodynamic calculations were made to provide a basis for predicting yields and the effects of the process parameters of temperature, composition, and pressure. The determination of the dependence of equilibrium Si yield by

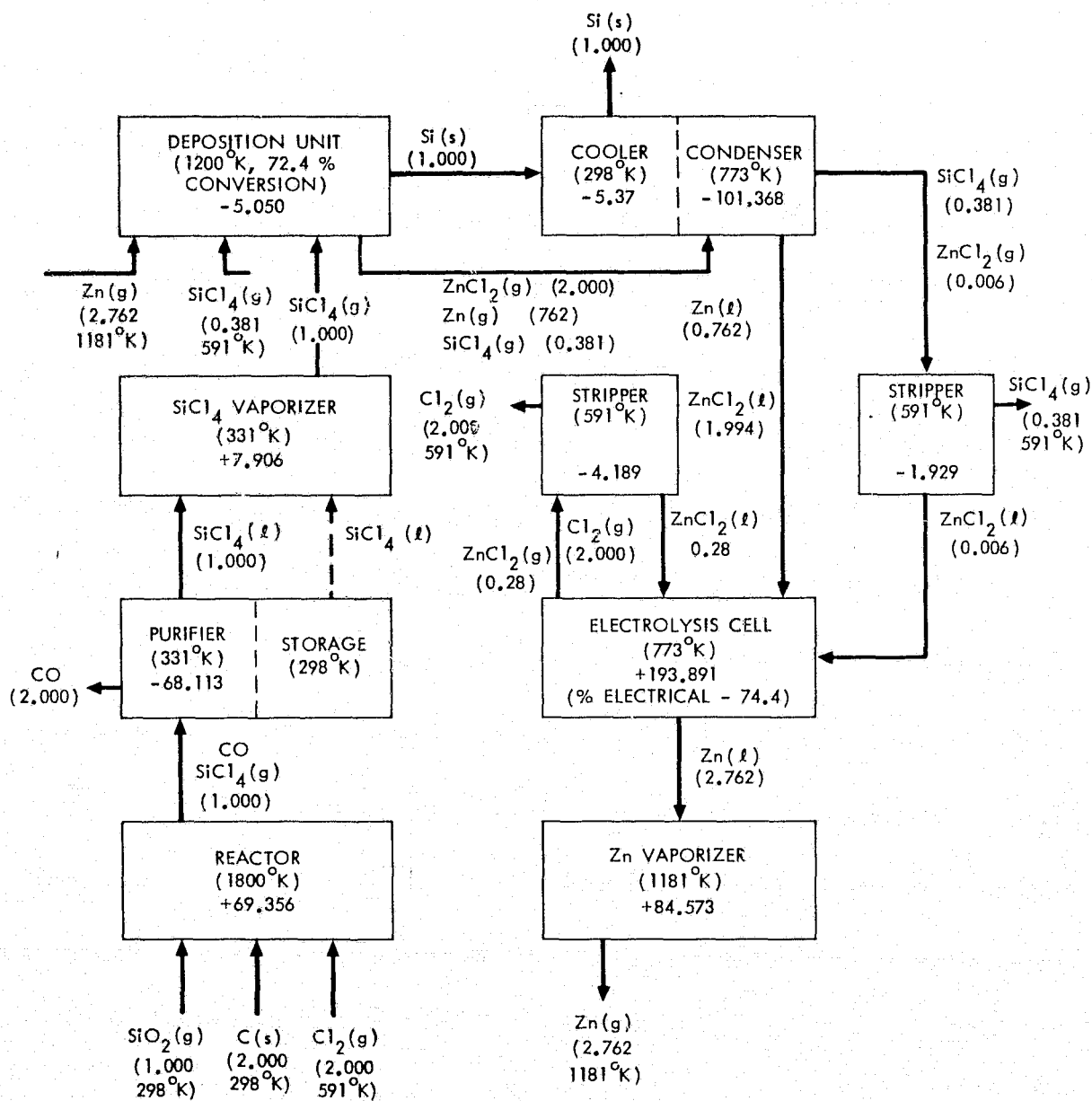


Fig. 4-4. Simplified energy and material flow chart for preparation of 1 mole of Si by reduction of SiCl_4

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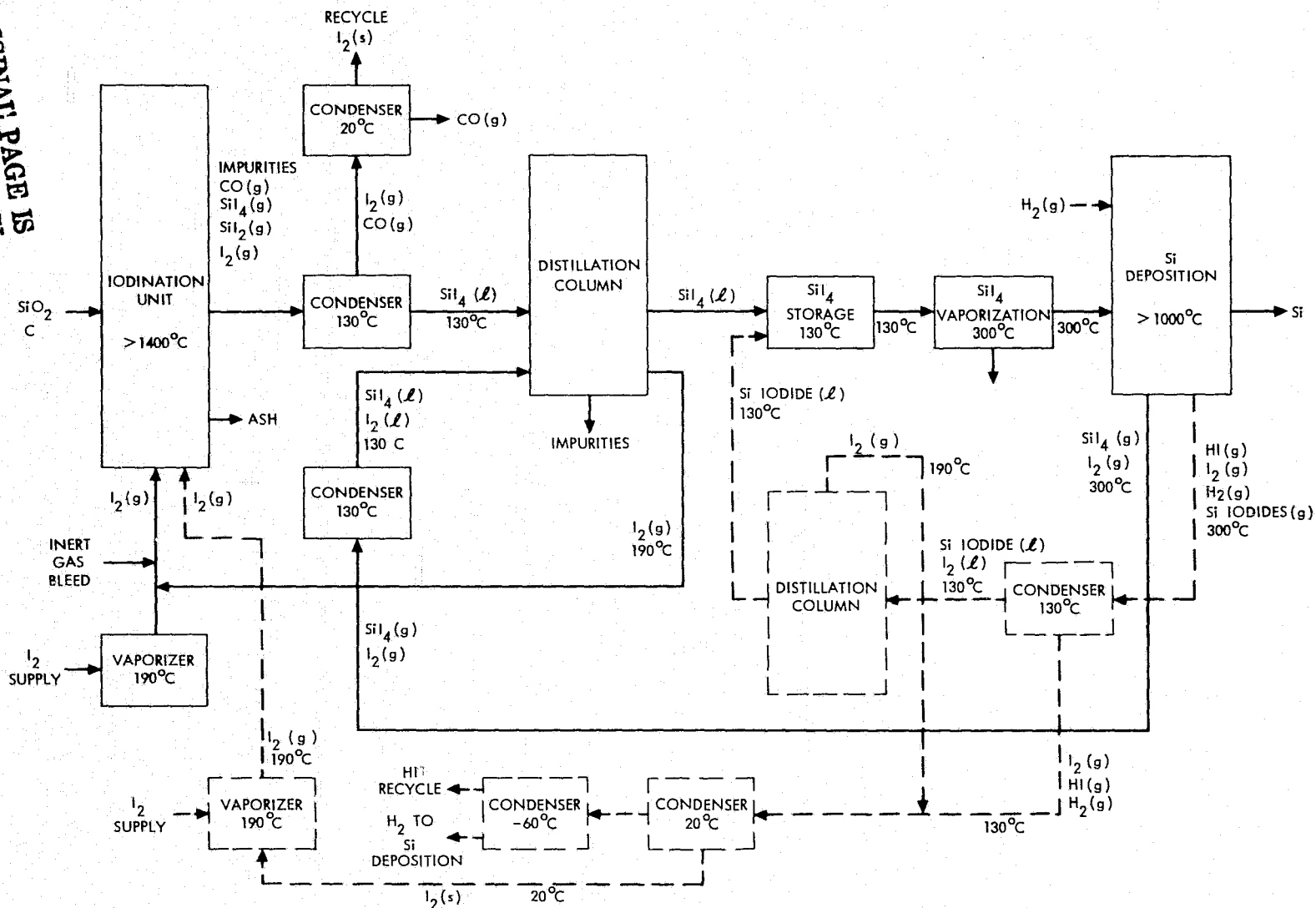


Fig. 4-5. Preliminary flow diagram for the preparation of Si from the hydrogen reduction pyrolysis of SiI₄ made by the iodination of SiO₂/carbon mixture

thermal decomposition of $\text{SiI}_4(\text{g})$ on temperature, pressure, and composition, revealed a large effect of pressure, which is a result of the increase in volume caused by the formation of monatomic iodine. Among the other conditions considered were: operation at a total pressure of one atmosphere, where the data indicate inefficient conversion at dilutions below 99/1 except at 1600°K ; operation at a total pressure of one atmosphere using H_2 as a reductant, where the yield decreases rapidly at H_2 dilutions below 19/1; the formation of SiI_4 by the iodination of SiO_2 -C mixtures, where the yields are low below 1600°K ; and the iodination of Si, where the reaction is essentially complete, yielding a mixture of SiI_4 , SiI_2 , SiHI_3 , and SiH_2I_2 in the temperature range of 800 to 1800°K . The effects of the addition of H_2 and a diluent gas were considered in several cases.

Thermal Decomposition of SiI_4 : Preliminary calculations of the energy and mass balances were made for the preparation of Si through the thermal decomposition of SiI_4 , as shown in Fig. 4-6. When no heat recovery is provided for, the energy requirement is about 13.3 kilowatt-hours per kilogram of Si; if all the heat is recovered, the value is about 6.3 kilowatt-hours per kilogram of Si.

Two procedures for the formation of SiI_4 were evaluated. The iodination of a SiO_2 -C mixture has been abandoned because of a high reaction temperature ($>1600^\circ\text{K}$) and a predicted costly recycle and separation procedure. Accordingly, the iodination of metallurgical grade Si, which has a conversion efficiency of about 100% will be studied.

The operating conditions considered were inert gas dilution and reduced pressure for the thermal decomposition reaction and H_2 reduction on a hot wire, a hot wall, and a fluidized bed. The experimental data for the H_2 reduction reaction indicate that the efficiencies are relatively high and that any of the deposition methods could be used.

Remarks: Several process factors remain to be determined before a comparison can be made between the decomposition of SiI_4 and the Zn reduction of SiCl_4 . Among these are the cost of the I_2 recovery; the procedure for

4-15

handling the HI; the performance of the fluidized bed; and the economic energy and yield for the SiH_4 process. Although the SiCl_4 process appears to be better at this stage, the final decision as to which process will be selected for a processing unit will depend upon an analysis of the sets of data now being obtained.

b. Production of SiH_4 by Redistribution of Chlorinated Silanes - Union Carbide

The objective of this program is to demonstrate the practicality of producing SiH_4 at a cost of \$3 to \$5 per kilogram using as the basic process the redistribution of a mixture of chlorinated silanes to yield SiH_4 . The redistribution is accomplished by using a tertiary amine ion exchange resin (Rohm and Haas Amberlyst A-21) for the catalytic disproportionation. This is followed by the purification of SiH_4 by fractional distillation, the chlorinated silanes being recycled and reprocessed. A second major effort is directed toward achieving direct synthesis of SiH_2Cl_2 to provide an enriched feed for the redistribution process step. To determine technical feasibility, the effects of temperature, pressure, and feed composition on rate, yield, selectivity, and purity will be investigated. These results will be incorporated into the calculations of mass and energy balances, the modeling of the full process, and economic and energy-use analyses. The first demonstration of the process will be conducted using a mini-plant, consisting of one redistribution reactor and one distillation column, to produce SiH_4 at the rate of 10 pounds per day for 10 days. The final demonstration will utilize a maxi-plant of two redistribution reactors and three distillation columns with the same production goal. A schematic of the maxi-plant is shown in Fig. 4-7.

Laboratory investigations are under way for studies of the redistribution of SiHCl_3 and SiH_2Cl_2 to SiH_4 , for the reaction of Cu/Si with HCl and H_2 using a fluidized bed reactor to produce a SiH_2Cl_2 -enriched mixture, and for the reaction of Si with H_2 and SiCl_4 to generate SiHCl_3 using a fluidized bed. In the first of this series of studies it has been shown that the yield on one pass was 13.5 mole percent from a SiH_2Cl_2 feed at 1 atmosphere and 60°C , a result which essentially corroborated early Union Carbide data. The recycling of unreacted SiH_2Cl_2 and by-product SiHCl_3 led to a stoichiometry of the overall

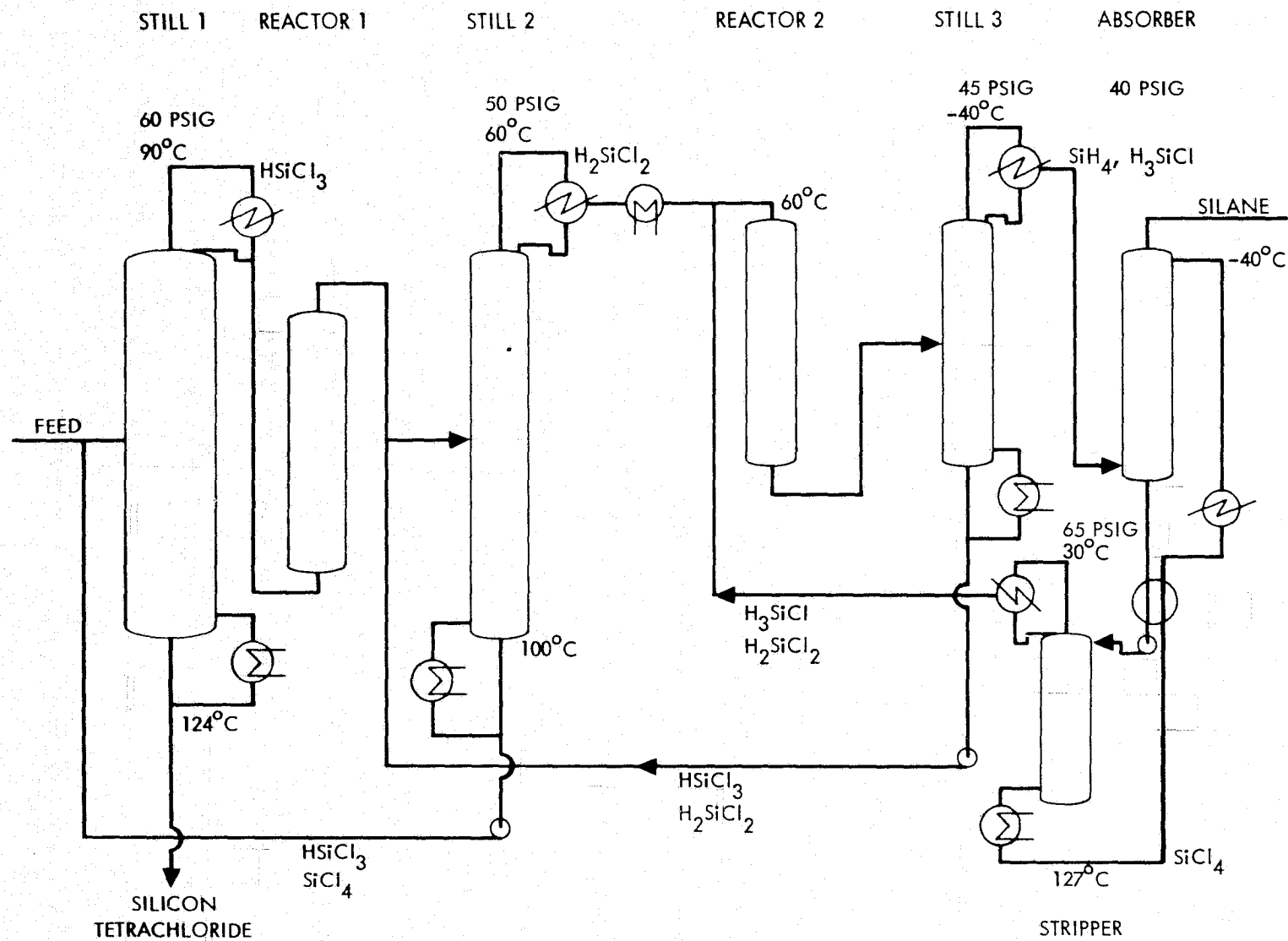


Fig. 4-7. Schematic for maxi-plant

disproportionation which can be written as: $3\text{SiH}_2\text{Cl}_2 \rightarrow 2\text{SiHCl}_3 + \text{SiH}_4$. Based on these data, the SiH_4 production rate was 0.27 pounds per hour per pound of A-21 resin with a feed of 4.2 pounds of SiH_2Cl_2 per hour. It is anticipated that this value, which is about 60% of the calculated rate, can be increased with improved component separations.

The design and planning for the mini-plant have proceeded on schedule. In support of the fractionation study, a compilation of information on the physical properties of the chlorinated silanes and SiH_4 has been made. The data for heat capacities have been compiled into equations by a least-squares treatment. The site is being prepared and the procurements of major equipment have been made. The plant is scheduled to be in operation in mid-1976.

c. Semiconductor-Grade Si Production by SiF_4 -
 SiF_2 Transport - Motorola Corporation

A contract has been negotiated for the development of the process to produce Si by the reaction of SiF_4 with metallurgical-grade Si to form SiF_2 as the transport species and then to deposit semiconductor-grade Si from a SiF_2 polymer, SiF_2 concurrently regenerating SiF_4 . The first phase of work under this contract will be directed toward the establishment of chemical feasibility, using the criteria of yield, rate, and purity. In the second phase chemical engineering calculations will be employed to provide evidence for practicality, energy-use, and economic analyses.

2. Specifications for Solar-Cell-Grade Si

The objective of Part II of Phase I (see Table 4-1) is to determine the effects of impurities in single crystal Si on the properties of the material and on the characteristics of solar cells. This effort will involve investigation of the interplay of impurities and the processes for preparing single crystal Si and for fabricating cells. (A concurrent effort in Parts I and III will be directed to studies of the impact of specific impurities on chemical reactions, purification requirements, production engineering, energy use, and price.) A series of

trade-offs will be required to establish the overall optimization of the technical and economic factors. A preliminary description of the influence of particular impurities on material and cell characteristics is scheduled for early 1977.

Westinghouse Electric and Monsanto Research are conducting programs to develop this information. These programs are nearly parallel in many respects. Thus, in each program doubly and multiply doped single crystals are being grown that contain one or more specific impurities in addition to the base dopant. The impurity matrices contain the elements Cr, Mn, Ni, Fe, Ti, V, Mg, Zn, and Zr. These crystals are to be characterized in a series of chemical, metallurgical and electrical measurements; solar cells are to be fabricated and evaluated; correlations are to be obtained between the impurities and impurity concentrations vis-a-vis the crystal material and solar cell properties; and impurity threshold levels are to be established. The programs differ in the following respects: Westinghouse will study the effects of relatively rapid crystal growth using the dendritic-web technique and Cu is included in its matrix. Monsanto will utilize the float-zone technique to contrast with the Czochralski-grown crystals in order to investigate the consequences of O and C concentrations; will examine the effectiveness of a sawed surface for gettering; and will include Al in the impurity matrix.

The analyses to be performed on the Si ingot include determinations of impurity concentrations, longitudinal resistivity, radial resistivity, dislocation density, and C and O concentrations. The wafers cut from the ingots are to be evaluated before and after processing. The evaluations made before processing consist of spreading resistance for composition homogeneity; optical microscopy, X-ray topography, and scanning electron microscopy for microstructure analysis; and photoconductive decay lifetime measurements. After cell fabrication, the performance characteristics of the cell are to be determined by measurements of lifetime, open circuit voltage, short circuit current, fill factor, spectral response, and efficiency.

a. Investigation of Effects of Impurities on Solar Cell Performance - Westinghouse Electric Corporation

Westinghouse Electric has completed preparation of the first generation ingots using the elements in the impurity matrix with the exception of Mg. The doping level was 10^{15} atoms/cm³, except for Ni which was 10^{14} atoms/cm³. A difficulty which occurred in first attempt to dope with Ni was subsequently overcome by the use of a Ni wire as the doping material in place of Ni powder. The evaluations of solar cells from wafers containing Cr, Mn, Cu, and Ni (10^{14} atoms/cm³) have been completed. The values of conversion efficiency obtained thus far are: 9.7% without impurity doping; 6.6 to 9.5% for Mn-doped; 8.5 to 9.5% for Ni-doped; and 9.0 to 9.8% for Cu-doped. In addition, wafers from baseline Si and Cr-, Mn-, Ni-, and Cu-doped ingots were delivered to JPL for evaluations.

In the next phase Westinghouse will prepare second-generation ingots with impurity concentrations set at 2×10^{14} atoms/cm³. The material and solar cell evaluations on the wafers from the first- and second-generation ingots will proceed.

b. Investigation of Effects of Impurities on Solar Cell Performance - Monsanto Research Corporation

Monsanto has completed preparation of crystals by float-zone techniques incorporating C, Fe (10^{15} atoms/cm³), Ni (10^{16} atoms/cm³), V (5×10^{15} atoms/cm³), Al (10^{17} atoms/cm³), and Zr (not yet determined), and has shipped slices to JPL for corroborating evaluations. Solar cells have been prepared and characterized; the efficiency measured for those prepared from baseline material was about 8%.

In the next phase Monsanto will complete the scheduled preparations of crystals and will proceed with the material and solar cell characterizations.

3. Processes for Producing Solar-Cell-Grade Si

The approach used for Part III of Phase I (see Table 4-1) incorporates theoretical studies involving thermodynamics, reaction chemistry, and chemical

engineering; chemical reaction investigations consisting of the experimental determinations of reaction kinetics, yields, and suitable process conditions; a chemical engineering effort for securing an experimental data base for preliminary process modeling; and energy-use and economic calculations for preliminary process models. In each case the contract requires a demonstration of technical feasibility and a projection of commercial practicality, involving the preliminary analysis of the suitability for a scale-up study. The evaluation of each process as a candidate for the scale-up studies (Phase II of Task 1) is scheduled for early 1977.

- a. Solar-Cell-Grade Si Production by Submerged-Arc-Furnace and Vacuum-Evaporation Processes - Dow Corning Corporation

A contract will be negotiated with Dow Corning for investigations of the submerged-arc-furnace and vacuum-evaporation processes for producing solar-cell-grade Si. The suitability of using purer raw materials will be explored using a development-size arc furnace. The application of the vacuum-evaporation technique will be examined using the products of the submerged-arc-furnace operation as the reactants. The final phase will include energy-use, product characteristics, and cost analyses for these processes.

- b. Solar-Cell-Grade Si Production by Duplex Vapor-Electro-Chemical Conversion of SiF_4 - Stanford Research Institute, Inc.

A contract will be negotiated with Stanford Research Institute for the investigation of a duplex vapor-electrochemical system for the use of an alkali metal to reduce SiF_4 to solar-cell-grade Si. The dependence of the yield and purity of the product on rates of reactions, mass transfer, energy use, temperature, pressure, flow rates, and reactor configuration will be determined. Chemical-engineering, economic, and energy-use studies will follow the phase to establish technical feasibility.

- c. Solar-Cell-Grade Si Production by C Reduction of SiO_2 in an Induction Plasma Torch - Texas Instruments Corporation

This contract with Texas Instruments is for the establishment of the feasibility of using an induction plasma torch to produce solar-cell-grade Si

from a reaction in which SiO_2 is reduced by C. The influence of C forms, gaseous environment, intimacy of mixing, rate of temperature rise, cooling, stoichiometry, thermodynamics, and kinetics on the yield and purity of the product will be investigated. A phase for chemical engineering studies is to follow the initial chemistry phase provided suitable reaction characteristics have been obtained. A final phase will be for energy and economic analyses.

4. Evaluation of Si Production Processes - Lamar University

Under Part IV of Task I (see Table 4-1), Lamar University is to perform investigations and analyses of the silicon-production processes being developed under Task 1. The objective of the program is to evaluate the relative commercial potentials of these processes. The economic evaluations are to be based upon analyses of process-system properties, chemical engineering analyses, and costing-economics.

The plan to be used for these evaluations involves the utilization of the results of the three analysis-sections for technical and economic comparisons of the alternative processes. The planning sequence then leads from these comparisons to the process selections and then to the phases of the task program for scale-up, for experimental plants, and for the commercial plant. At each stage, these analyses and evaluations are to continue, utilizing the new information which becomes available from the various process-development contracts.

The analyses of the process-system properties which are to be performed will lead to physical and chemical descriptions of the processes. Data are being collected from the literature, independent sources, and from laboratory measurements on vapor pressure, latent heat of vaporization, heat capacity, density, viscosity, thermal conductivity, enthalpy of formation, and Gibbs free energy of formation. The subsequent analyses of engineering design, construction, start-up, operation, and process optimization will make use of this information base.

The chemical engineering analyses to be conducted will be used to calculate the kinetic and practical yield properties of the process. These analyses will include preliminary process flow diagrams, descriptions of the reactions, kinetic rate data, major equipment activities, chemical equilibrium considerations, mass transport, heat transfer, concentration effects, temperature effects, and reactor configurations. Investigations leading to the conditions for optimizing the commercial production properties of processes will be based on the models built from these chemical engineering data.

In performing the economic analyses, the items to be considered will include process flow diagrams, capital investment estimates, manufacturing costs, raw material costs, material balances, energy balances, construction and maintenance, and staffing. The economic models will be optimized for low price and low energy use as well as high production.

The preliminary data collection from domestic sources for the process-system properties analyses is nearing completion for the Si source materials associated with the SiH_4 , SiCl_4 , and SiI_4 processes. Requests for information from foreign sources have been issued. An additional effort dealing with the SiF_4 transport process has been initiated.

As part of the chemical-engineering-analysis effort, an extensive information exchange with the Task 1 contractors is under way; this was started at the recent Project Integration Meeting. The following set of baseline conditions was established for use in the analysis of a commercial plant to produce solar cell grade Si: (1) plant size - 1000 metric tons per year; (2) cost index - capital equipment cost is to be based on the January 1975 cost-index value, 430; (3) operating ratio - the operating ratio should be selected based on the assumed operating days per year.

In the economic analysis effort, a considerable amount of data for use in capital cost estimation was obtained. An extensive list of equipment usable in the processes to be analyzed has been assembled. The assignments of the equipment to the various processes and the calculations for preliminary models of the processes are continuing.

The next period will include efforts to complete the compilation of data sources on Si source materials; to perform additional data analyses for physical, thermodynamic, and transport properties; to proceed with data assembly and preliminary descriptions of the various processes; and to review methods for estimating plant fixed capital investment based on major process equipment capital costs.

5. JPL Task 1 In-House Support

Subprograms which are complementary and supporting to the contractual efforts will be under way at JPL throughout the Task 1 program. These subprograms include measurements and evaluations of (a) materials and cells associated with the contracts of Part II and (b) chemical intermediates and products from the reactions under development in the contracts of Parts I and III. In addition studies of the fluidized bed process will be conducted in cooperation with the development contracts of Parts I and III, which incorporate this process technique.

The measurement of the properties of Si materials and cells provides an independent set of data to be used to corroborate the correlations obtained by the contractors. Three categories of measurements will be used: chemical, metallurgical, and electrical.

Chemical measurements will be for the purpose of determining the chemical composition of reaction products in the process developments and of ingots and slices in the solar cell grade definition effort. The sensitivity needed is in the ppba to ppma range. This sensitivity can be obtained for different groups of elements using spark source mass spectroscopy, atomic absorption spectroscopy, and neutron activation analysis.

Metallurgical analyses will be performed for the purpose of correlating the structural properties of slices and cells with the chemical constitution of the material and with the electrical performance characteristics of solar cells.

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These analyses require the use of optical microscopy (dislocation density and structure), transmission electron microscopy (clusters, vacancies, and precipitates), scanning electron microscopy (topographic defects), Laue X-ray diffraction (crystal orientation), and X-ray topography (structure defects).

Electrical measurements will be made for the purpose of correlating the electrical parameters important to solar cell performance with chemical constitution and structural properties.

Studies of fluidized bed technology form the second major in-house subprogram, since a fluidized bed reactor is a primary element in the Si deposition step of the process developments by Battelle and Union Carbide. The common basis for this emphasis is the recognition of the inherent advantages of a fluidized bed reactor for some processes when compared with the commercial CVD process for the deposition of Si. These advantages include very small heat losses, temperature uniformity, the capability of large production rates because of the large surface area and high gas flow rates which can be used, and the suitability for continuous operation. The JPL in-house program in this field will be designed to support and be complementary to the contractual efforts.

Some of the aspects to be investigated at JPL will be as follows: (1) theoretical thermodynamic and kinetic studies of fluidized bed SiH_4 deposition reactions; (2) models for fluidized bed operation, especially for small particle size seeds; (3) temperature profile measurements; (4) characterization of particles as a function of time and operating conditions; (5) studies of fluidization conditions not covered by the contracts; and (6) determinations of chemical engineering data, which can be used for mass and heat balances, reaction kinetics, Si deposition modeling, and engineering cost estimates. The results of these investigations will be evaluated concurrently with the progress under the contracts and should provide the information base for more complete development efforts in this field.

The in-house subprograms are under way. Preliminary fluidized bed studies are being accomplished in the areas of basic feasibility analyses; fluidized bed models; bench scale experiments; and theoretical studies of reaction kinetics, chemical analyses, mass and heat transfer, and fluid mechanics.

The in-house measurements include the determinations of minority carrier lifetimes in cell blanks and in processed solar cells, of resistivity profiles, and of solar cell performance characteristics, e. g., I_{sc} , efficiency, and spectral response.

TASK 2. LARGE-AREA SILICON SHEETS

The objective of the Large-Area Silicon Sheet (LASS) Task is to develop and demonstrate the feasibility of several alternative processes for producing large areas of silicon sheet material suitable for low-cost, high efficiency solar photovoltaic energy conversion. To meet the objective of the LSSA Project, sufficient research and development must be performed on a number of processes to determine the capability of each for producing large areas of crystallized silicon. The final sheet-growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

A. TECHNICAL BACKGROUND

Current solar cell technology is based on the use of silicon wafers obtained by slicing large Czochralski or float-zone ingots (up to 12.5 centimeters in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single crystalline silicon wafers is tailored to the needs of large volume semiconductor products (i. e., integrated circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of silicon "real estate" production techniques which would result in low-cost electrical energy.

Growth of silicon crystalline material in a geometry which does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e. g., hexagonal cross-sections), requiring very little manpower and machinery would also appear

plausible. However, it appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

B. ORGANIZATION OF THE TASK 2 EFFORT

At the time the LSSA Project was initiated, in January 1975, a number of methods potentially suitable for growing silicon crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured.

The Task 2 effort is organized into four phases: research and development on sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); development, fabrication, and operation of production growth plants (1983-86).

C. TASK 2 CONTRACTS

The pursuit of optimal techniques for growing silicon crystalline material for solar cell production has led to the awarding of R&D contracts to 10 organizations. The processes being developed by these contractors are shown in Table 4-3.

Figure 4-8 shows the schedule for each contract as it was initially negotiated. Follow-on work anticipated for each contract is indicated by the cross-hatched horizontal bars. Research and development work will continue through the end of FY 1977, by which time it is expected that technical feasibility will have been demonstrated. It is anticipated that two additional R&D contracts will be awarded during late FY 1976 or early FY 1977 for other growth process candidates. Selection of "preferred" growth methods for further development during FY 1978-80 is planned for late FY 1977 or early FY 1978. By 1980, both technical and economic feasibility should be demonstrated by individual growth methods.

Table 4-3. Task 2 contractors

Contractor	Technology Area
RIBBON GROWTH PROCESSES	
IBM, Hopewell Junction, New York	Edge-defined, film-fed growth
Mobil-Tyco, Waltham, Massachusetts	Edge-defined, film-fed growth
Motorola, Phoenix, Arizona	Laser zone ribbon growth
RCA*, Princeton, New Jersey	Inverted Stepalov growth
Univ. of So. Carolina, Columbia, So. Carolina	Web-dendritic growth
SHEET GROWTH PROCESSES	
General Electric, Schenectady, New York	Floating substrate (chemical vapor deposition on liquid)
Honeywell, Bloomington, Minnesota	Dip-coating (on low-cost substrates)
Rockwell, Anaheim, California	Chemical vapor deposition (on low- cost substrates)
INGOT GROWTH AND CUTTING	
Crystal Systems, Salem, Massachusetts	Heat-exchanger ingot casting and multiple wire sawing
INGOT CUTTING	
Varian, Lexington, Massachusetts	Breadknife sawing
Univ. of Pennsylvania*, Philadelphia, Pennsylvania	Hot-forming of silicon
* Contract to be awarded in Spring of 1976.	

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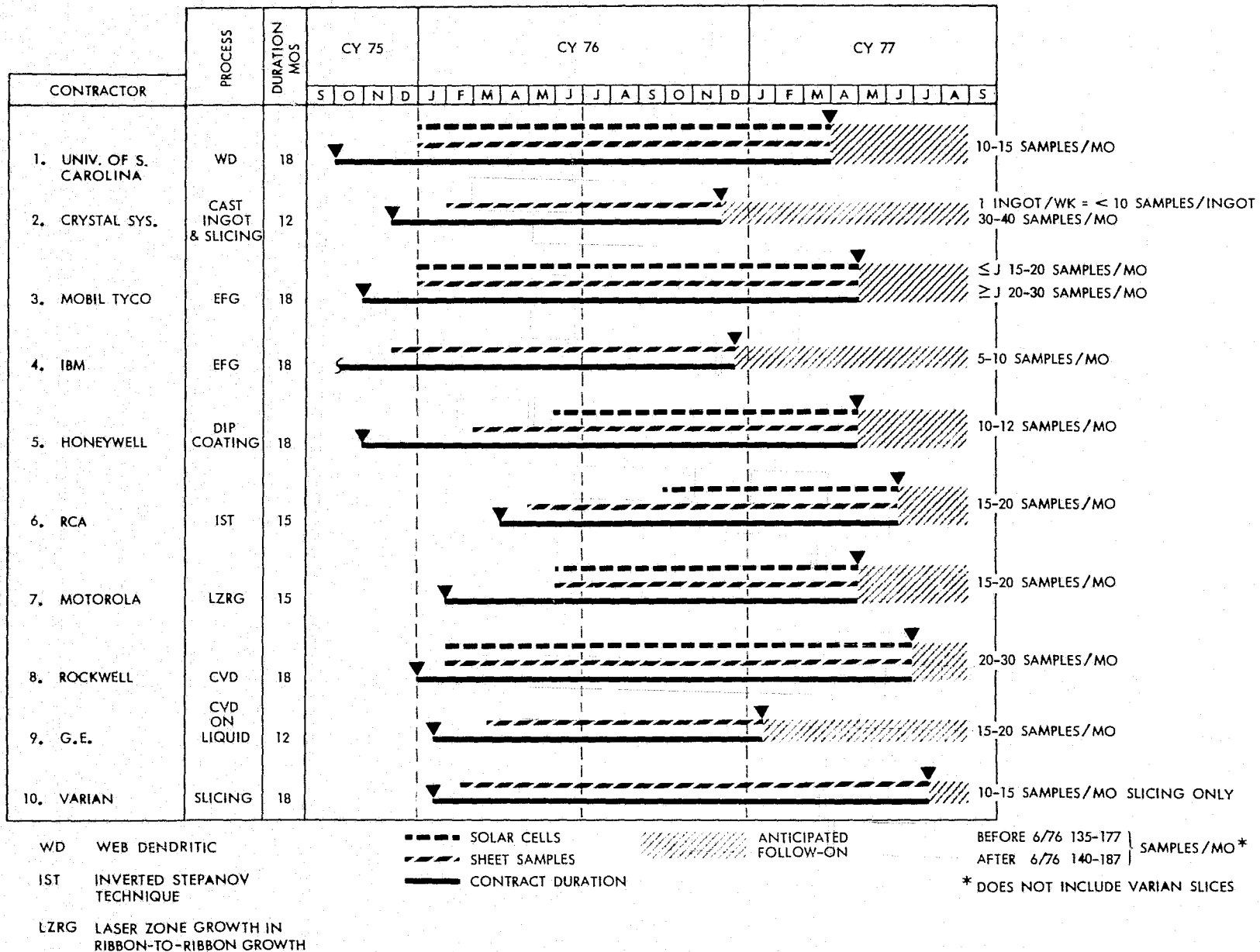


Fig. 4-8. Large Area Silicon Sheet Task schedule

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Figure 4-8 also indicates the receipt of silicon "sheet" samples and solar cells from the various growth-process R&D programs. These samples/solar cells will be characterized/evaluated at JPL.

D. TASK 2 TECHNICAL ACTIVITY

Information regarding each growth-process R&D contract is given in the following pages. Each process is briefly described, together with a short account of what the individual contracts are designed to accomplish in order to demonstrate technical feasibility. Accomplishments to date plus future plans are also given (except for RCA, whose contract is still under negotiation at the time of this writing).

1. Web-Dendritic Growth - University of South Carolina

Web-dendritic growth makes its own guides of silicon, whereas most other ribbon processes must rely on materials other than silicon for the guides (i.e., dies) (Fig. 4-9). The guides are thin dendrites that grow ahead of the sheet and support the molten silicon between them to form the sheet. The dendrite guides grow in a very precise orientation dictated by their unique growth habit. Thus the orientation of the sheet which grows between them takes on this precise orientation. The twin plane reentrant edge mechanism (TPREM) controls the growth of the edge dendrites, giving them their unique and internally-controlled growth direction allowing them to grow ahead of the sheet and thus acts as guides.

The basic steps, then, in web sheet growth are (1) dip a seed of the proper orientation into a slightly undercooled melt, (2) hold the seed stationary while growth takes place laterally on the surface of the melt, forming what is termed the button and (3) when the lateral growth has proceeded to the desired width, start the pulling. As the pulling proceeds, two coplanar dendrites grow downward from each end of the button, propagating to a depth of 1-3 millimeters beneath the surface of the melt. As the button and its dendrites emerge from the melt, silicon is pulled up between them by surface tension, and the resulting sheet solidifies just above the melt surface. The unique orientation and slight undercooling to insure faceted growth give the sheet its almost mirror-flat surface finish.

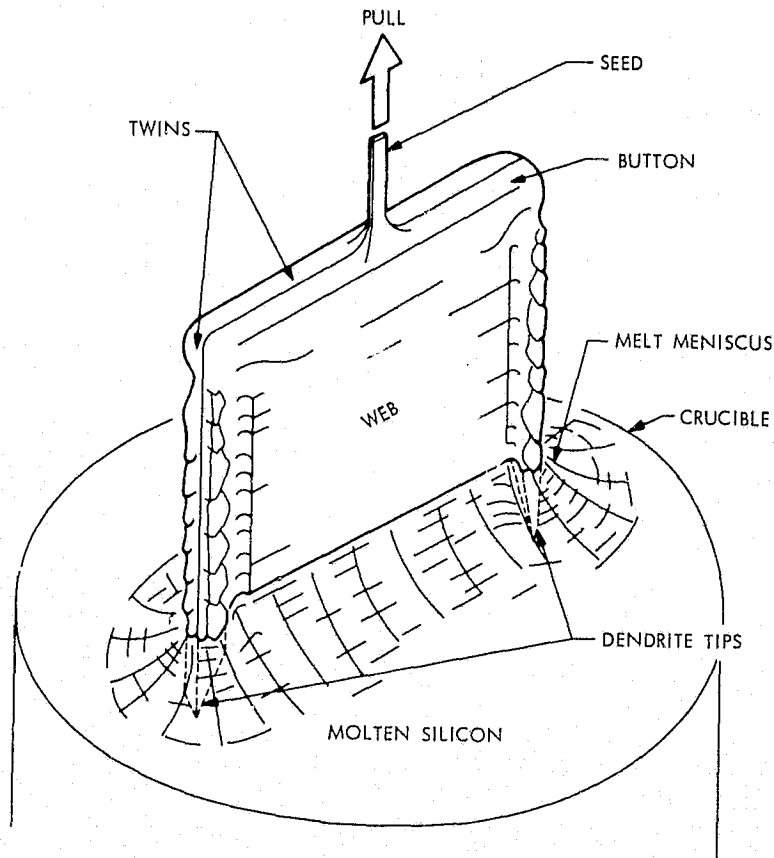


Fig. 4-9. Web dendritic growth

The overall goal of this contract is to develop a better understanding of the web-dendritic process and define in greater detail the basic limitations of the process (especially the maximum growth rate and width). This will be accomplished by development of a multivariate semiempirical model of the web-dendritic growth process based upon growth experiments and theory.

The contractor has set up the crystal growth apparatus and has grown some small web-dendrite ribbons. The major problem to date has been improper thermal gradients in the melt, causing nucleation of a third dendrite. Modifications to change the thermal gradients have begun. A concurrent analysis of thermal stability of the meniscus under static conditions has been made. In the characterization area, solar cells have been made from commercial Czochralski wafers. Some preliminary work has been started on transmission and scanning electron microscopes to measure twin spacing.

Plans for the next quarter include defining the thermal geometry for growing wider ribbon. This will include analytical heat flow analysis and correlation of the heat transfer rate with crystallization kinetics and seeding requirements. More detailed characterization of bulk web silicon and solar cell fabrication from web material is scheduled for the next quarter.

2. EFG Growth - Mobil-Tyco Solar Energy Corporation

Efforts under this contract are directed toward extending the capacity of EFG growth of silicon sheet to speeds of 3 inches a minute and widths of 3 inches; work began November 1975 (Fig. 4-10). The initial stages will involve independent development of high-speed growth (with appropriate thicknesses) and improved width. Later stages will attempt to integrate these two approaches. The experimental program involves two machines and will be supported by appropriate theoretical analyses of the liquid/solid die configuration and the thermal geometry surrounding the crystallization and cooling of the ribbon. Appropriate characterization and solar cell preparation is included.

At present, the EFG growth machine for the development of faster growth of appropriate thicknesses is producing ribbon at speeds approaching the planned 3 inches per minute. These ribbons are highly stressed and not full-width (less than 1 inch), but are indicative of significant progress. Studies on this machine have demonstrated that the $(110) \langle 211 \rangle$ orientation offers a specific advantage for EFG growth in that seeding may be achieved with this orientation. A parallel twin structure in the grown ribbon is still obtained regardless of whether the seed is a single crystal or twinned, and perturbations to this parallel twin structure are still being introduced by the silicon carbide particles coming from the die. However, these results do indicate the higher stability of this structure and orientation. Theoretical studies are presently addressing the problem of stress within the ribbon and results thus far suggest it to be a significant problem for high-speed growth. Other effort at this time involves the initial design for the second machine, planned to demonstrate 3-inch wide growth. The second machine will have a horizontal configuration consistent with eventual melt replenishment studies.

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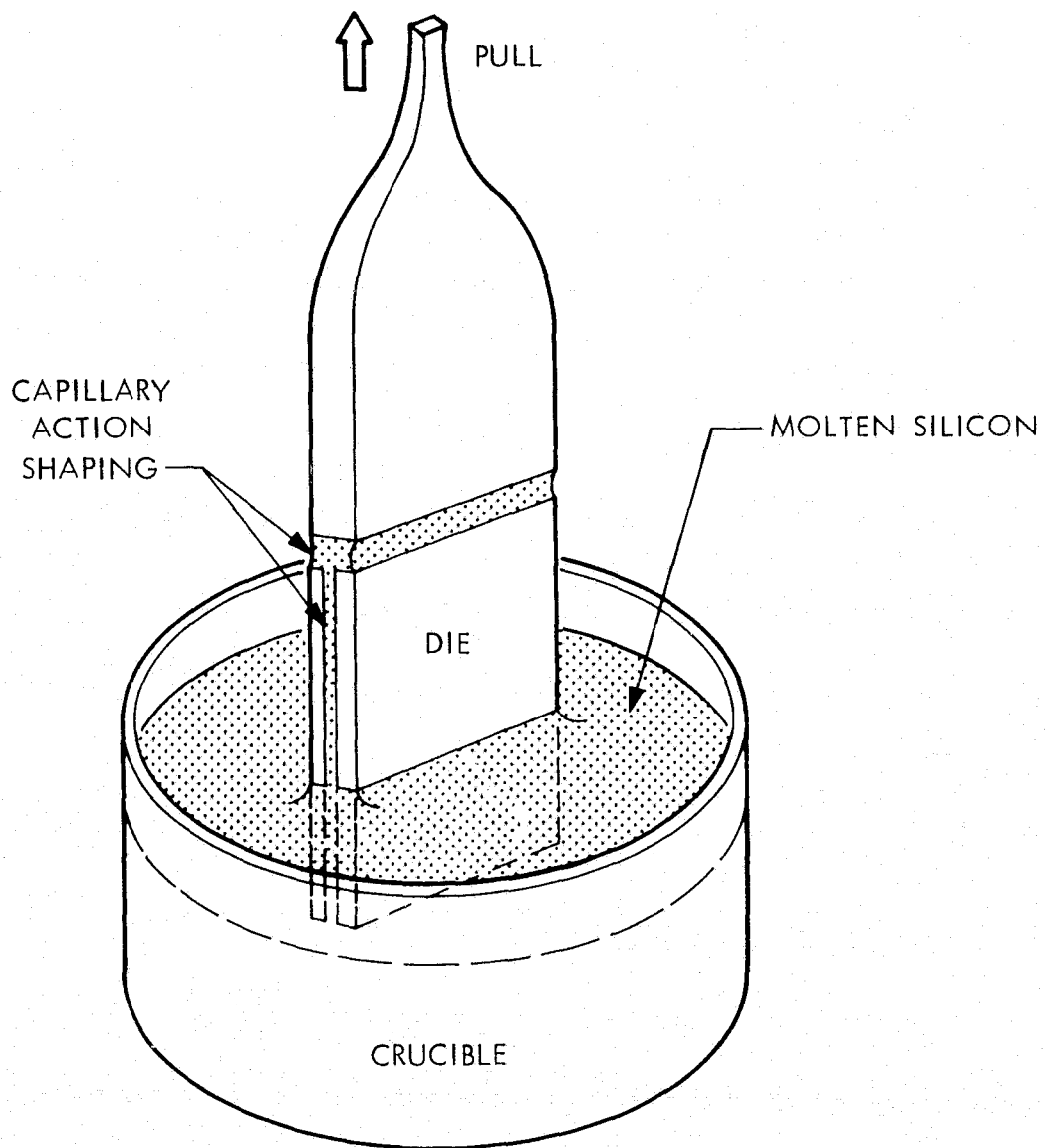


Fig. 4-10. Capillary die growth

Near-term plans involve further efforts toward improving the quality of the fast-grown ribbon by incorporating implications of the stress and thermal analysis into the experimental configuration. Characterization and solar cell preparation is under way and preliminary results will be evaluated soon. A final design for the wide-ribbon machine will be selected and construction begun.

3. EFG Growth - IBM

The contract is directed toward the assessment of EFG as a means of producing silicon ribbon suitable for solar cells, characterization of that ribbon, and economic analysis of a number of means of producing silicon sheet (Fig. 4-10). The ribbon growth by EFG involves both experimental and theoretical studies of the process. The characterization is primarily electrical and structural but does not specifically include solar cell preparation. Characterization also includes the development and assessment of new techniques. The economic studies include development of software for the assessment of potential costs for producing silicon and ribbon sheets as a function of input and processing parameters.

The program has been under way since May 1975, and the EFG work at present includes the capacity to grow nominally 1-inch-wide material but has included the growth of tubes and an assessment of the velocity/thickness relationship under such growth. Studies also include several alternate die materials; however, results in this area have not yet been conclusive.

Characterization work at present has identified the carbide particles formed within the ribbon as Beta silicon carbide, and a brownish film on the surface as SiO plus Si resulting from the decomposition of SiO. Electron channeling techniques have also been investigated as a means of structure determination. The computer work at present has resulted in software for economic analysis of EFG growth and work has begun on Czochralski growth.

Near-term plans will include studies of stress distribution and crystal perfection as a function of the thermal geometry surrounding the ribbon.

Characterization effort will emphasize correlation of structural defects in the EFG ribbon with lifetime as measured from MOS capacitors. Work on the economic models for various sheet growth techniques will continue.

4. Inverted Stepanov Technique - RCA

In this program emphasis is placed on the development of the growth of ribbon-shaped silicon using a "non-wetted" die (Fig. 4-11). The use of the "non-wetted" die provides the possibility of minimizing the reaction between the molten silicon and the die material. Reaction between molten silicon and wetted dies is one source of degradation in the crystallographic quality of silicon grown using a wetted die (i.e., the edge-defined film-fed growth method). The introduction of the feed from above and the growth of the single crystal in a downward direction (the inverted Stepanov technique) in part compensates for the hydrodynamic drag in the slot and for the lack of capillary rise. (The capillary rise feeds the material to the die edge in the EFG method.) The inverted geometry also leads to considerable flexibility in the growth configuration when the feed is introduced from a molten zone at the end of a solid silicon rod.

The primary objective of the program is to investigate the basic seeding and growth processes involved in the growth of silicon sheet from "non-wetted" dies. The goal is to establish whether or not significant improvement in the crystallographic properties of the silicon can be realized by the use of "non-wetted" rather than "wetted" shaping dies. Silica and boron nitride shaping dies will be used. Methods will be sought to compensate for the lack of mechanical strength of silica at the growth temperature. Although boron nitride leads to unacceptable doping of the grown silicon ribbon, it is more rigid than silica and therefore is useful in the identification of fundamental limiting factors in the Stepanov growth method.

5. Laser-Zone Growth in a Ribbon-to-Ribbon Process - Motorola Corporation

The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline silicon ribbon (Fig. 4-12).

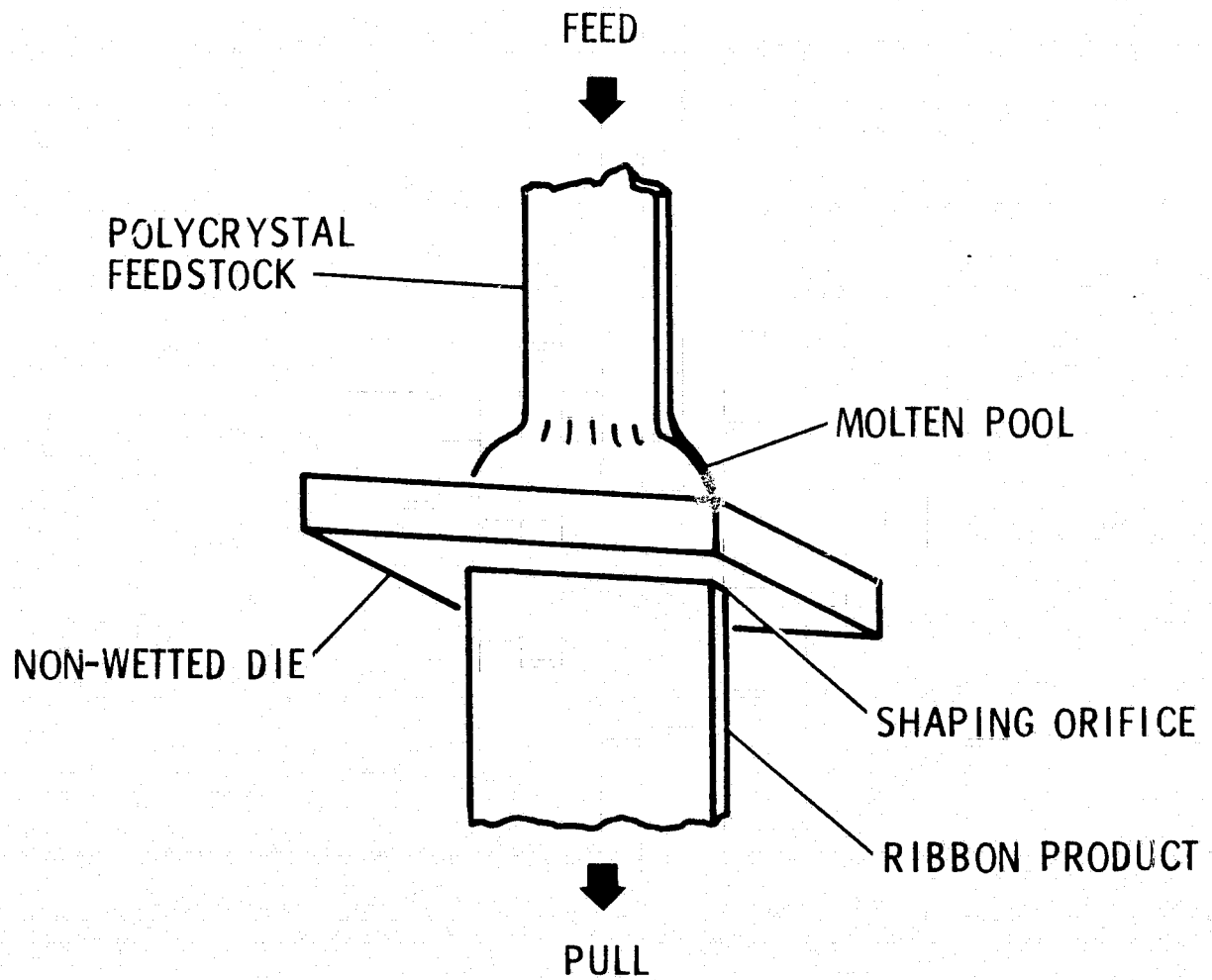


Fig. 4-11. Inverted Stepanov technique - RCA

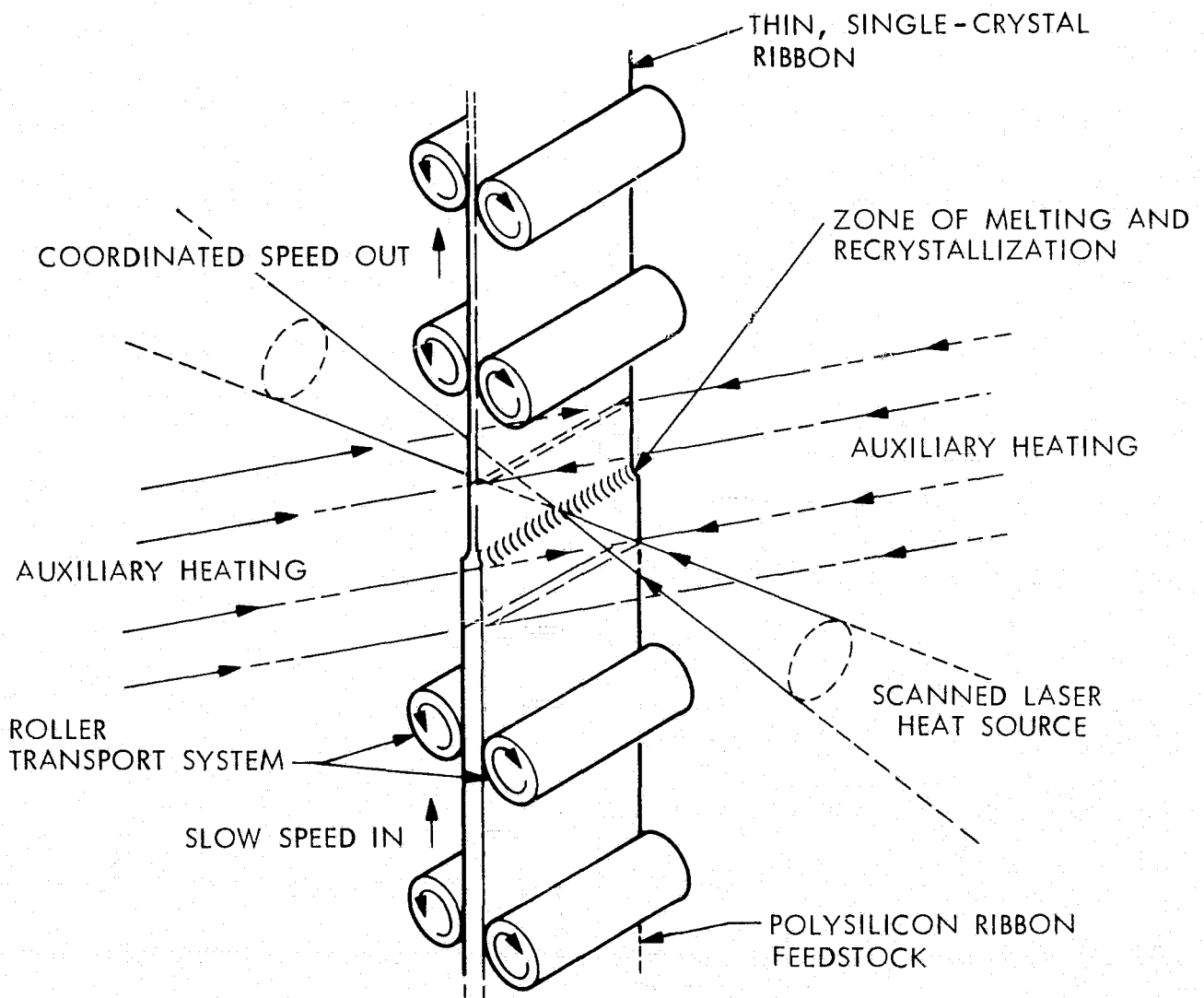


Fig. 4-12. Laser zone crystallization

The polysilicon ribbon is fed into a preheated region which is additionally heated by a focused laser beam, melted, and crystallized. The liquid silicon is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

This is a contract of 15 months duration; the primary efforts under it are to:

- Modify and evaluate the existing ribbon-to-ribbon growth facility to meet the contract goals.
- Operate the facility on a regular basis to study and optimize the growth capabilities of the RTR process with particular emphasis on thermal environment, seeding, ribbon velocity, laser input configuration, and throughput.
- Perform characterizations/tests on ribbon samples from each growth run.
- Fabricate and characterize solar cells.

This contract was entered into on February 4, 1976. To date, Motorola has submitted the program plan detailing the various efforts listed above. The plan is being reviewed by JPL.

The plans for the next quarter call for completion and evaluation of the RTR growth facility. Some of the particular modifications which will be completed and evaluations which will be performed are:

- Design and implementation of auxiliary heating techniques.
- Installation of a new camera viewing system which will allow sample viewing from front, rear and at least one side simultaneously.
- Installation and calibration of optical pyrometer and photodiode temperature sensors.

- Completion of translation programmer necessary for higher speed growth runs.
- Installation of a remote mirror orientation control system to ensure ability of alignment of laser scans.

During this time various other aspects of the system will be evaluated to ensure proper operation; e. g., ribbon translation staging, laser operational characteristics (beam profiles, power optimization, power control, etc.) and the optical system.

6. CVD on Low-Cost Substrates - Rockwell Corporation

The purpose of this contract is to explore the chemical vapor deposition (CVD) method for the growth of silicon sheet on inexpensive substrate materials (Fig. 4-13). The work will be carried out at the Rockwell Electronics Research Division in Anaheim, but also involves experimental solar cell fabrication and evaluation by the Photoelectronics Group to Optical Coating Laboratory, Inc., in City of Industry, California. The contract provides for an 18-month effort. Work started on December 29, 1975; this report covers the first 2 months.

The CVD method as applied to silicon sheet growth involves pyrolysis, or reduction, of a suitable silicon compound at elevated temperature and approximately atmospheric pressure in a flow-through (open-tube) deposition chamber in which the substrate is mounted on a silicon carbide-coated carbon pedestal heated by rf from outside the chamber. The properties of the silicon sheet are determined by deposition temperature, reactant concentrations, the nature of the carrier gas, the silicon source compound used, growth rate, doping impurities (added by introduction of appropriate compounds into the carrier gas stream), and the properties of the substrate.

The specific technical goals established for the contract include the following:

Silicon sheet:

Area (per sample)	30 cm ²
Deposition rate	5 μm per minute

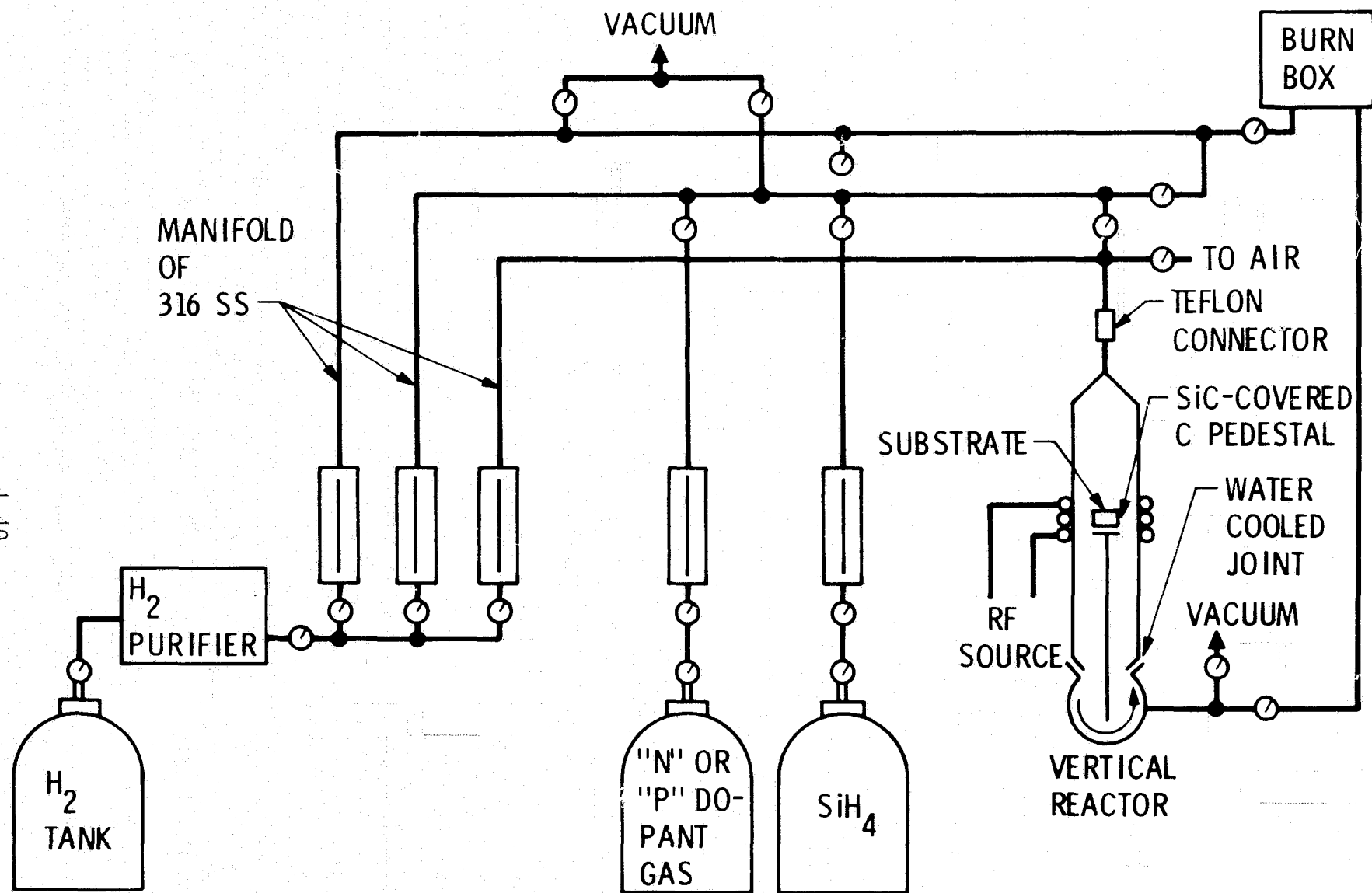


Fig. 4-13. Chemical vapor deposition (CVD) - Rockwell International

Thickness	20 to 100 μm
Crystal structure	100 μm average grain size
Intragrain dislocation density	$< 10^4$ per cm^2

The contract program is structured in terms of six main technical tasks, as follows:

- Modification and test of an existing CVD reactor system.
- Identification and/or development of suitable inexpensive substrate materials.
- Experimental investigation of CVD process parameters using various candidate substrate materials.
- Preparation of silicon sheet samples for various special studies, including solar cell fabrication.
- Evaluation of the properties of the silicon sheet material produced by the CVD process.
- Fabrication and evaluation of experimental solar cell structures by Optical Coating Laboratories, Inc., using standards and near-standard processing techniques.

Design details of modifications to the CVD reactor have been finalized and all of the parts required have been ordered; however, because of long delivery times, the modifications may not be complete until April. This should not impact the program because the unmodified reactor will be adequate until the "fine-tuning" stage of process control is reached.

Several candidate substrate materials (glasses and ceramics) have been acquired and Dr. H. Manasevit has visited seven potential suppliers in search of more. Several of them expressed strong interest in supplying nonstandard glasses, ceramics, glazes, and metallized materials. As some of the substrates tested so far have proved to be reactive in an H_2 carrier gas but not in He, deposition parameters for the latter are being established.

By the end of the next quarter, the reactor modification should be complete and experiments to define the deposition and doping parameters well under

way. Techniques for X-ray and scanning-electron-microscope determination of grain size and orientation should be established and spreading-resistance measurement capability acquired.

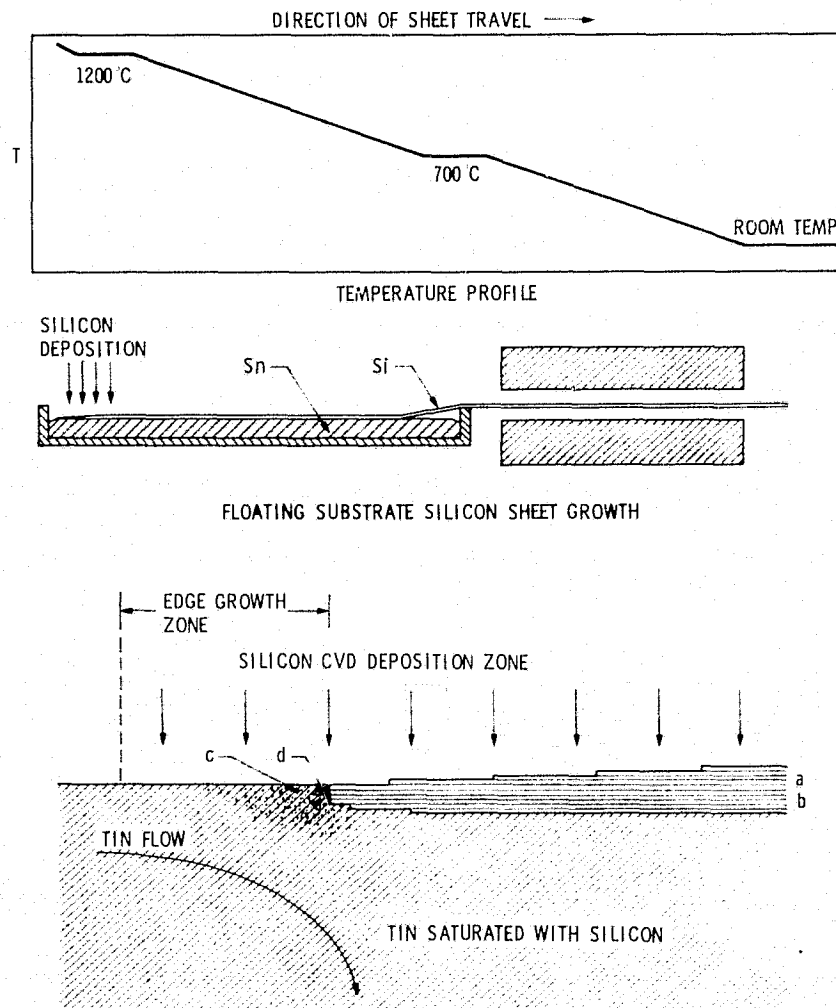
7. Floating Substrate/CVD on Liquid - General Electric

The purpose of this contract is to demonstrate the feasibility of a floating substrate sheet growth process for the fabrication of silicon sheet (Fig. 4-14). The process is an approach to the formation of single crystal silicon by direct epitaxial conversion from gaseous silane. In an appropriate reactor, silane is passed over silicon substrate which is supported on a thin film of molten tin. Single crystal silicon grows to the desired thickness by vapor phase epitaxy. Nucleation of fresh substrate silicon takes place at one end of the reactor where the edge of the growing sheet is in contact with a region of the tin which is super-saturated with silicon. The process lends itself to continuous operation, with the finished sheet being withdrawn from the opposite end of the growth zone.

The contract covers a 15-month program intended to provide a feasibility-of-concept demonstration. The major portion of the program will focus on nucleation studies and the rapid growth of silicon substrate from supercooled melts. These efforts should lead to a sheet growth demonstration by the end of the first contract year and a design and cost analysis for a prototype sheet growth apparatus by contract close. Explicit studies for the contract include:

- Supercooling in Sn-Si melts.
- Crystal growth from a supercooled Sn-Si melt.
- Silicon uptake by tin from silanes.
- Surface growth.
- Prototype design and cost analysis.

The technical goals for the contract require growth of a single crystal of silicon having an area of 0.5 cm^2 and the determination of the propagation velocity of single crystal silicon growth along a supersaturated hot tin melt surface.



ENLARGED SCHEMATIC VIEW OF GROWING EDGE OF SHEET. (a - FIRST FEW ATOMIC LAYERS OF EPITAXIALLY DEPOSITED SILICON, b - THIN LOWER LAYER FORMED BY GROWTH FROM SILICON SOLUTION, c - SURFACE OF LIQUID TIN SUPERSATURATED WITH SILICON BY DEPOSITION FROM VAPOR PHASE, AND d - LEADING EDGE)

Fig. 4-14. Floating substrate sheet growth - GE Research and Development Center

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To date, the experimental apparatus for the supercooling and silane uptake experiments have been designed and fabricated. The supercooling apparatus has been assembled, is operational, and experiments are under way. The silane uptake apparatus is in final assembly. Progress appears satisfactory.

Scheduled activities for the next quarter include completion of the basic studies of supercooling and silicon uptake from silanes and the initiation of studies of crystal growth from supercooled Sn-Si melts.

8. Dip-Coating on Low-Cost Substrates - Honeywell Corporation

This program is directed toward the evaluation of silicon films crystallized from the melt on low-cost ceramic substrates (Fig. 4-15). Ceramics have been selected because of their superior thermal expansion match with silicon and the greater ease with which this expansion may be adjusted. The ceramics will be coated with a film of carbon or silicon carbide to enhance the adhesion. The concept has been demonstrated previously. The total program includes construction of a dipping facility, selection and evaluation of substrates and associated coatings, production of dip films and their characterization by various structural, chemical and solar cell performance methods. The solar cells will require some specialized techniques because of the nonconductive nature of the substrate.

The program was initiated in late October and to date has emphasized the design and construction of the dipping facility. It has been completed and has melted some silicon, although minor difficulties with the power supply have prevented melting a full charge at this time. Effort has also been expended in the procurement and preparation of suitable ceramic substrates. Approximately 25 different substrate structures and compositions have been obtained, ranging from dense polycrystals to pressed papers. In addition, some effort has been expended on the development of solar cell fabrication techniques suitable for front-side contacting. However, this work is presently incomplete.

Short-term plans provide for beginning the dip-coating operation as soon as the minor power supply problem has been corrected. Initial substrates will

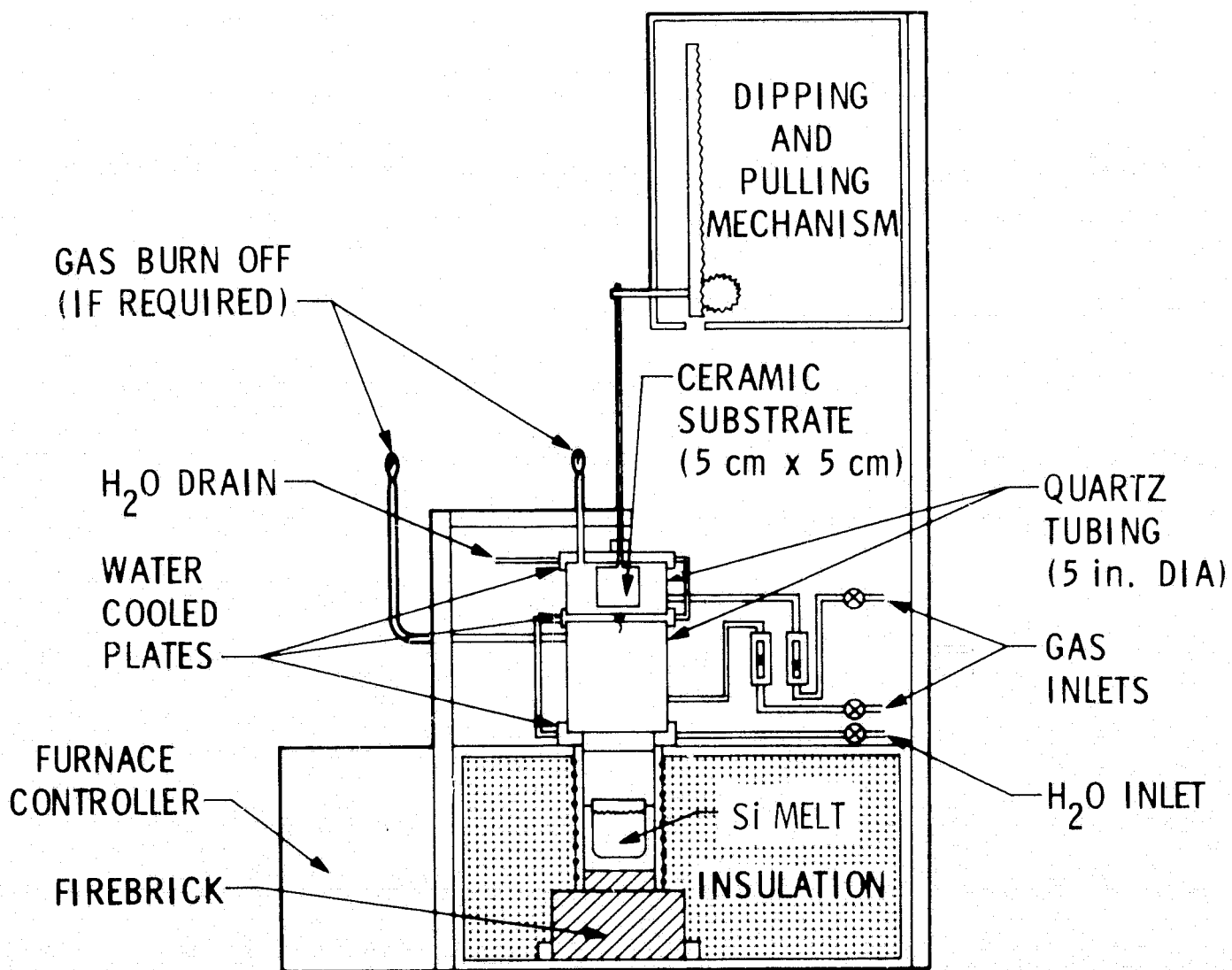


Fig. 4-15. Cross-sectional sketch of basic sheet dip coating growth facility - Honeywell Corporate Research Center

be carbon coated by mechanical scrubbing to reproduce past efforts. Other coating techniques will be used to provide a matrix of variables of substrates and coatings. In this manner the controlling features of nucleation and growth can be ascertained. Efforts involving the cell preparation methods will also continue.

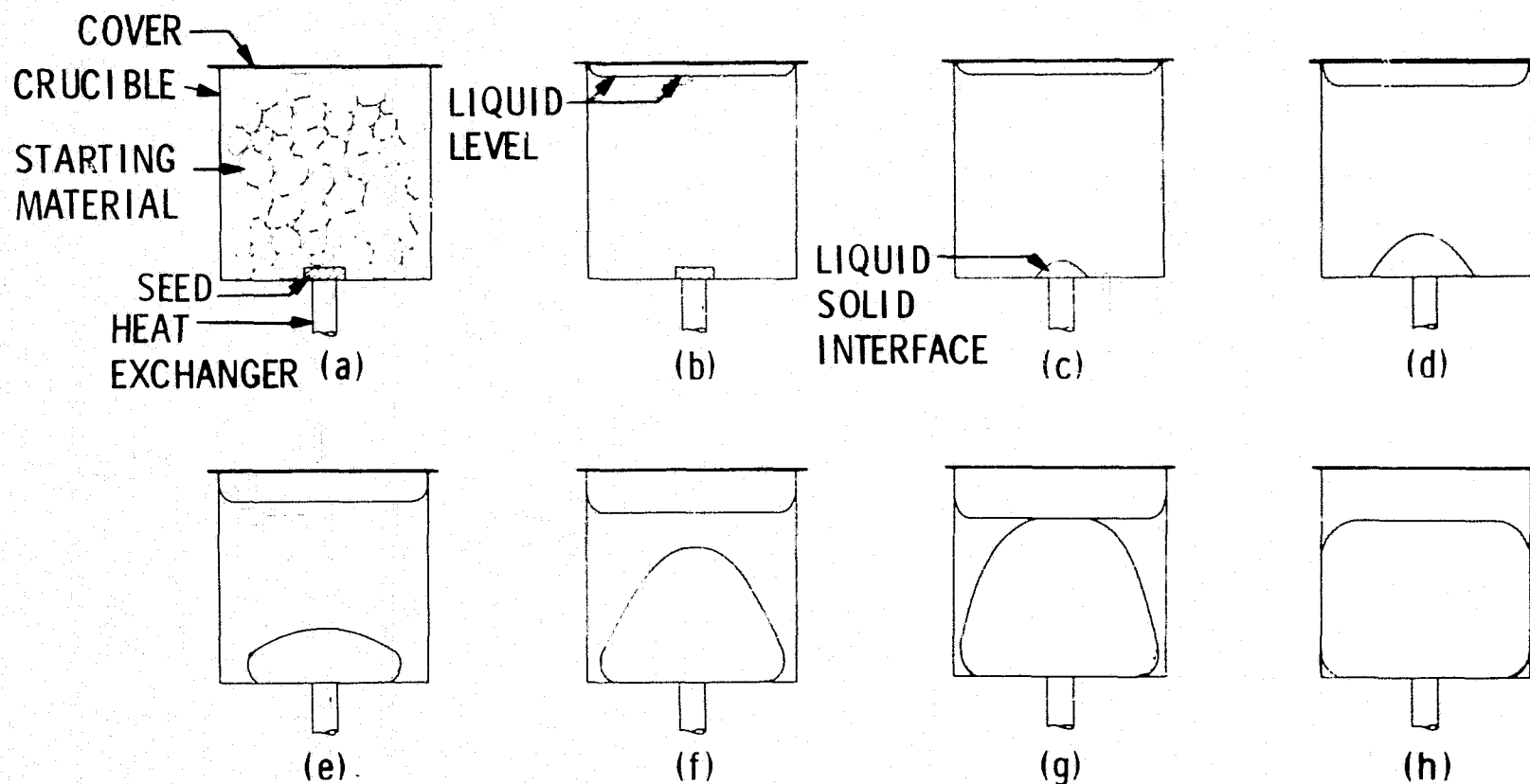
9. Heat Exchanger Method of Ingot Casting - Crystal Systems, Inc.

The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Fig. 4-16). Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchanger ingot casting method can grow large silicon crystals (6 inches in diameter by 4 inches in height) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire growth technology (50-pound ingots have already been grown), and by theoretical consideration of seeding, crystallization kinetics, fluid dynamics, and heat flow for silicon.

Five silicon-crystal castings have been made to date. Crystal Systems has melted and frozen as much as 2500 grams of silicon, but has not yet produced a single-crystal casting. Directional freezing of one sample demonstrated large directionally-textured grains. Since the casting is being done under partial vacuum pressure, the contractor has made some theoretical calculations of the oxygen and CO pressures versus temperature.

During the next quarter the establishment of seeding conditions for growing 6 x 4 inch single crystals will be undertaken. The conditions will be achieved through a semi-empirical approach that considers known sapphire



GROWTH OF A CRYSTAL BY THE HEAT EXCHANGER METHOD (HEM). (a) CRUCIBLE, COVER, STARTING MATERIAL, AND SEED PRIOR TO MELTING; (b) STARTING MATERIAL MELTED; (c) SEED PARTIALLY MELTED TO INSURE GOOD NUCLEATION; (d) GROWTH OF CRYSTAL COMMENCES; (e) GROWTH OF CRYSTAL COVERS CRUCIBLE BOTTOM; (f) LIQUID-SOLID INTERFACE EXPANDS IN NEARLY ELLIPSOIDAL FASHION; (g) LIQUID-SOLID INTERFACE BREAKS LIQUID SURFACE; (h) CRYSTAL GROWTH COMPLETED

Fig. 4-16. Crystal growth using the Heat Exchanger Method (HEM)
Crystal Systems Inc.

technology, silicon wetting technology, heat transfer, and crystallization kinetics.

10. Multiple-Wire Sawing - Crystal Systems, Inc.

Today most silicon is sliced into wafers with an inside diameter saw, one wafer at a time being sliced from the crystal. This is a big cost factor in producing solar cells. The lesser-used multiblade slicer can be utilized to slice silicon. The multiblade slicer has not been developed for the semiconductor industry since this method produces bow and taper unacceptable for integrated-circuit applications.

The overall goal of the slicing program is to optimize multiblade (wire) silicon slicing, investigating the following parameters in particular:

- Rate of material removal and kerf removal.
- Slice thickness, wire blade dimensions, cutting, forces, wire/blade tension, and other machine variables.
- Wires versus blades as a cutting tool.
- Variation of rocking motion.
- Introduction of abrasive during slicing operation.
- Effect of surface condition of tool, including consideration of hardness and method of plating.
- Effect of diamond abrasive particle size and type.
- Effect of cutting fluid composition.

A rocking mechanism weighing only 1/10 of the original sample holder mechanism has been fabricated. This modification was required since the original mechanism was too heavy, causing large inertia and high friction during slicing of the sample. A diaphragm seal with low friction is utilized to control the force which the work piece exerts on the wire.

During the next quarter, investigation will emphasize this rocking mechanism to study the parameters listed above. A special emphasis will be

placed on including sodium hydroxide in the cutting media at temperatures greater than room temperature to increase the cutting rate. Wire sizes (50 wires/run) will be 0.003 and 0.008 inch.

11. Breadknife Sawing - Varian Corporation

The purpose of this contract is to develop a multiple-blade sawing process that will significantly reduce the cost of cutting wafers from ingots or blocks of single crystal silicon for solar cell fabrication and has the potential to be scaled up for eventual large production environments (Fig. 4-17). The major portion of the program consists of a systematic experimental investigation of:

- Variation in cutting loads.
- Speed of slicing head.
- Blade dimensions.
- Abrasive, size, and concentrations.
- Blade material properties and costs.
- Lubricants.
- Specimen mountings.

The investigations will be conducted on a Varian 686 wafering machine which will be modified for experimental studies. It will be supplemented by a parallel theoretical effort to parametrize system performance as affected by modified abrasive wear and to establish practical limits to wafer accuracy and thickness, blade instability, abrasive blunting, etc. The major technical goals for the program are:

- | | |
|------------------------------|--------------------|
| ● Wafer thickness: | 5 mils |
| ● Slicing rate: | 10 mils per minute |
| ● Kerf loss: | 5 mils |
| ● Number of parallel slices: | 100 |
| ● Stock size: | 4 inches |

Work to date includes (1) modification of a Varian 686 wafering machine for cleaner slurry drainage; stronger, shock-free drive system; and a smoother

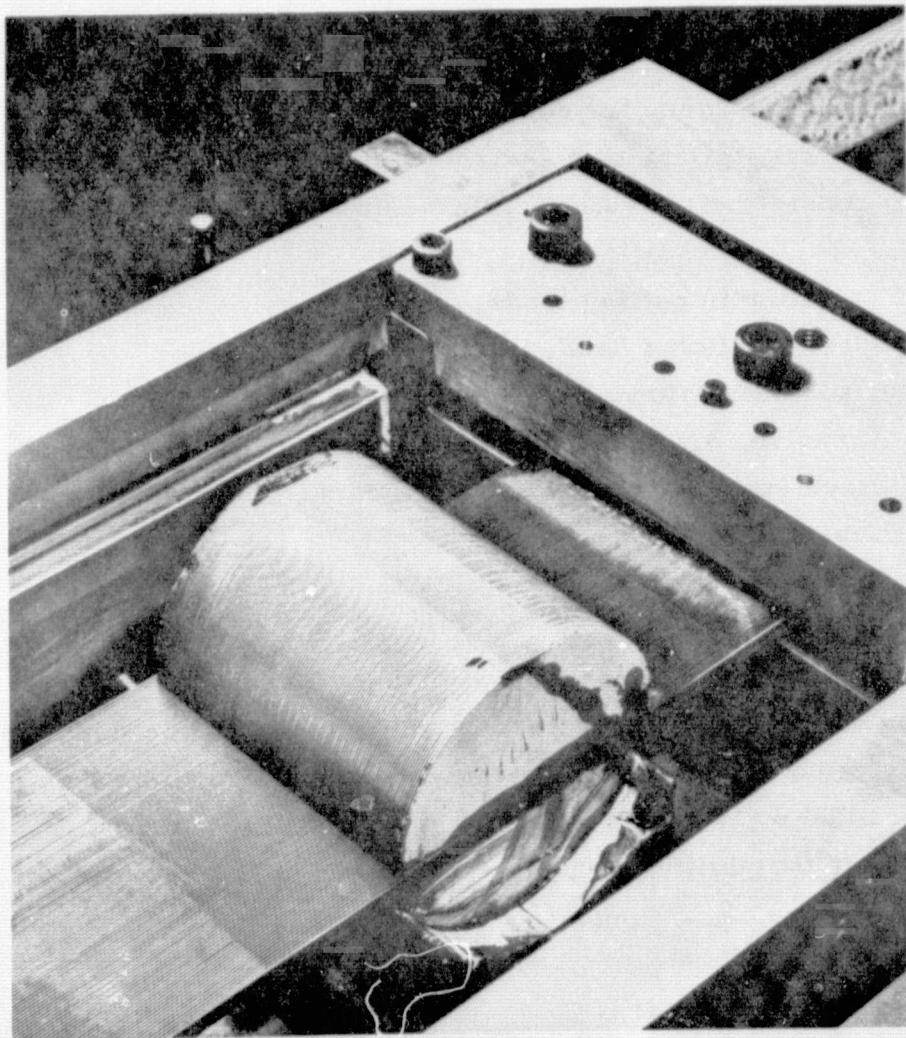


Fig. 4-17. Three-inch diameter silicon in Varian multiblade wafer saw

acting vertical feed; (2) initiation of theoretical studies for slurry sawing; and (3) preliminary design considerations for a load-balancing dynamometer for the wafering machine. The first ingots for wafering have been purchased and slicing experiments are under way.

The next quarter's activities will be to complete the saw modifications (including the dynamometer), continue with the slicing tests and theoretical modeling of abrasive wear, and initiate development of a feedback control system to regulate cutting rate and force interactions.

12. JPL In-House Task 2 Activity

a. Silicon Characterization

Structural and electrical characterization of material samples received from the growth contracts (see Fig. 4-8) will be performed at JPL. The basis for this work is the definition of characterization techniques which meet the individual needs of each growth method being developed for high efficiency solar-photovoltaic energy conversion. Characterization tests will be run on individual samples using at least the following techniques:

(1) Structural Characterization.

- X-ray (Laue, topography, Debye-Scherrer, etc.)
- Scanning electron microscope (reflection, EBIC, EDAX (impurities)).
- Optical microscopy (grain structure, defects, surface topography, etc.).

(2) Electrical Characterization.

- Lifetime/diffusion length (capacitive time-delay, surface photovoltage, electron voltage).
- Resistivity (spreading resistance, four-point probe).

- Hall measurements (mobility, carrier concentration).
- "Thermal" spectroscopy (deep level trap spectroscopy; thermally stimulated current or capacitance).

Other analytical techniques will be added as deemed necessary during the program (e.g., transmission electron microscopy, electroreflectance, etc.). Routine characterization of material using specific techniques which will have been determined to be meaningful for specific forms of silicon (e.g., EBIC for examining grain boundaries in CVD layers) will be done on a contract basis. This will allow for a larger sampling of material than is either possible or necessary during the initial stages of each growth contract.

TASK 3. ENCAPSULATION

The objective of the Encapsulation Task is to develop and qualify a solar array module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments. In addition, significant technical problems are anticipated at interfaces between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections. Selection of the element for the rear side (i. e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

Depending on the final solar array design implementation, the encapsulation system may also serve other functions, e. g., structural, electrical, etc. - in addition to providing the essential protection.

At present, options are being kept open as to what form the transparent element of the encapsulation system will take - glass or polymer sheet, polymer film, sprayable polymer, castable polymer, etc. The transparent element may contain more than one material and may be integral with the photovoltaic device, or be bonded to it, or installed as a window or lens remote from the device.

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A. TECHNICAL BACKGROUND

Photovoltaic devices (solar cells) and the associated electrical conductors which together constitute solar arrays must be protected from exposure to the environment. Exposure would cause severe degradation of electrical performance as a result of corrosion, contamination, and mechanical damage.

In the recent past, limited testing by JPL, NASA-LeRC, the U.S. Coast Guard, and solar cell manufacturers has clearly demonstrated that arrays must be protected from the terrestrial environment and confirmed that spacecraft array encapsulation system designs do not provide adequate protection. At the same time this test experience has indicated that there are no known technical barriers to designing encapsulation systems which will withstand longlife terrestrial exposure. To be acceptable, the encapsulation system must be compatible with low-cost, high-volume cell and array production methods.

B. ORGANIZATION OF THE TASK 3 EFFORT

The approach to be used in achieving the overall objective of Task 3 will include an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations will be conducted to assure timely accomplishment of objectives.

During Phase I the contractor and the JPL in-house effort will consist primarily of a systematic assessment and documentation of the following items:

- Potential candidate encapsulant materials based on past experience with the encapsulation of silicon and other semiconductor devices and on available information on the properties and stability of other potential encapsulant materials and processes.
- The environment which the encapsulation system must withstand.
- The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.
- Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

The results of this effort will then be used to specifically define additional research, development, and evaluation required during the subsequent phase.

Throughout the task atypical or unique approaches to solving the encapsulation system problem will be sought and evaluated. For example, Phase I will include an evaluation of the feasibility of utilizing electrostatically-bonded integral glass covers as part of the encapsulation system.

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulation systems and then verify the expected lifetime and reliability of these systems. Depending on the results of Phase I, the contractor effort in this phase will include an appropriate combination of some of the following items:

- Evaluate, develop, and/or modify test and analytical methods and then validate these methods.
- Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.
- Modify materials and processes used in encapsulation systems to improve automation and cost potential.
- Modify potential encapsulation system materials to optimize mechanical, thermal and aging properties.
- Implement research and development on new encapsulant materials.

C. TASK 3 CONTRACTS

During the past year a contract with Battelle Columbus Laboratories was initiated to perform the following investigations:

- 1) Identification of candidate encapsulant materials based on a review of (a) worldwide experience with encapsulation systems for silicon solar cells and related devices and (b) the properties of other available materials.

- 2) Definition of conditions for evaluating and qualifying encapsulant materials based on analysis of environmental information.
- 3) Evaluation of test methods and determination of properties of candidate encapsulant materials.
- 4) Development of accelerated and/or abbreviated test and analytical methods for evaluating encapsulation systems.

Additional contractors (see Table 4-4) have been selected for the following activities, scheduled to begin approximately April 1, 1976:

- DeBell and Richardson. A study of the properties, processing, and aging of polymeric encapsulant materials and the use of high-stress testing to evaluate encapsulation systems utilizing these materials.
- Rockwell International. An experimental evaluation of accelerated/abbreviated testing methods. This will complement the analytically oriented effort at Battelle.
- Simulation Physics, Inc. An examination of the feasibility of utilizing electrostatically-bonded integral glass covers as the transparent part of the encapsulation system.

The sequence of these activities during the Phase I is shown in Fig. 4-18. During the first year the only contractor activities have been in first two studies under the Battelle contract.

D. TASK 3 TECHNICAL ACTIVITY

1. Identification of Candidate Encapsulant Materials – Battelle Memorial Institute

In this study, possible encapsulation system requirements were reviewed to bracket the possible range of requirements for encapsulant materials. Some of the most widely used encapsulant materials were identified. Based on this information and selected keyword identifiers, a major literature search has been undertaken to identify and retrieve relevant information. Various standard

Table 4-4. Task 3 contractors

Contractor	Technology Area
Battelle Memorial Institute Columbus, Ohio	Encapsulant experience and definition of environment; encapsulant test methods and capabilities
DeBell and Richardson* Enfield, Connecticut	Polymeric properties and aging studies
Rockwell*, Anaheim, California	Accelerated/abbreviated testing
Simulation Physics* Burlington, Massachusetts	Bonded integral glass covers
*Contracts to be awarded in spring of 1976.	

data bases, as well as several special bibliographies, have been interrogated. The output of these searches has been reviewed by materials specialists to identify and select documents for detailed review. To date over 600 documents have been identified and ordered; approximately 500 have been received and 200 reviewed.

The magnitude of this review requires that relevant data be extracted the first time through each document. At the same time the current lack of definition of the final array configuration (concentration, tracking, flat, etc.) makes it necessary to extract information on a broad spectrum of materials.

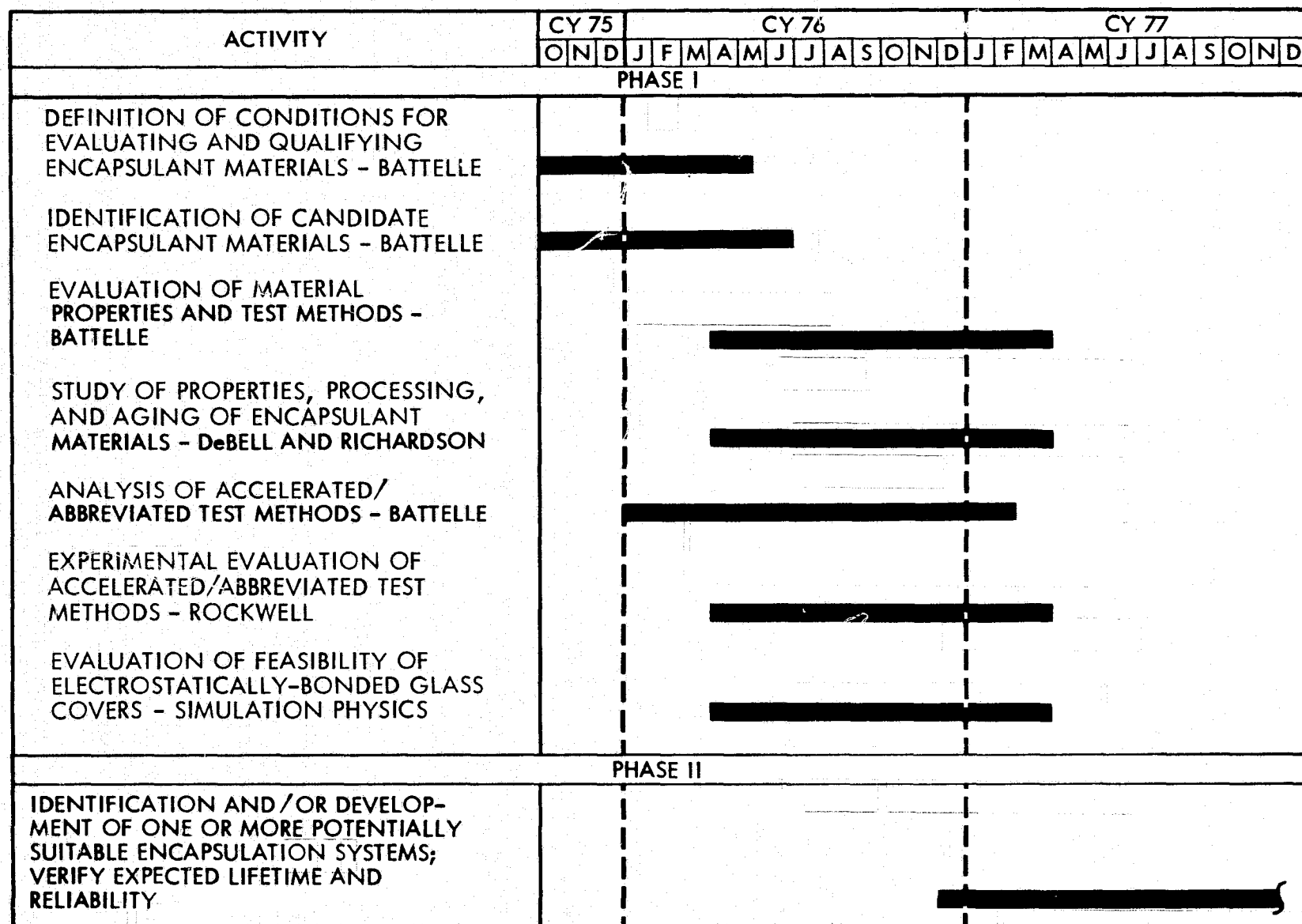


Fig. 4-18. Encapsulation task schedule

2. Conditions for Evaluating and Qualifying Encapsulant Materials – Battelle Memorial Institute

In this study, the expected frequency and duration of combinations of environmental conditions during the 20-year array lifetime will be used to establish test conditions for the encapsulation system. Since combinations of conditions govern degradation, rather than individual extremes or distributions, historical record data from selected sites are being analyzed for the simultaneous occurrences. Twenty-year predictions will be developed using standard statistical methods.

The following nine sites were selected because (1) they are representative of United States climatological extremes and of geographical areas where large scale photovoltaic installations might be used and (2) suitable data about them is available:

Phoenix	Semiarid, high insolation, moderate altitude
Albuquerque	Semiarid, high insolation, high altitude
Miami	Semitropical, marine, high humidity, high average temperature
Bismarck	Low winter temperatures, large seasonal variations
Cleveland	Pollution, high humidity, snow, climatic mixtures
Los Angeles/ Riverside	Pollution, high diurnal temperature variation
Fairbanks	Low average temperature, extreme low temperatures, large seasonal variations
San Antonio or Brownsville	Warm climate, high insolation
Boston/Blue Hill	Moderately cold, humid, fog, marine

After evaluating possible approaches, an existing program, the Statistical Program for the Social Sciences (SPSS), was selected for use in the analysis of historical data. With this program the range of each climatic condition

(temperature, relative humidity, etc.) can be divided into selected intervals and the statistics of simultaneous occurrence (of various combinations and transitions) determined.

During the past year a trial analysis of one of the sites was completed for temperature, relative humidity, wind velocity, and insolation. Of the 600 possible combinations (with selected intervals), less than 200 occurred during the 10-year period analyzed. (This confirmed the expectation that considerably fewer than 600 should occur, since climatic conditions are not independent variables.) Furthermore, of a preliminary set of 34 "abusive" conditions (i. e., combinations of conditions that would be expected to cause above-average degradation of the encapsulation system), only 12 occurred during the 10-year period and represented approximately 5-1/2 percent of the total time. Thus, for this site, the (preliminary) "abusive" conditions would represent slightly over 1 year during the 20-year array lifetime.

Since the parameters, combinations, and intervals can easily be changed for a variety of applications, the methodology that has been developed is expected to be useful to the Project Analysis and Design and Test portions of the Project. To accommodate these activities and to permit analysis of additional sites (if required after the Battelle study of the conditions for evaluating and qualifying encapsulant materials is completed), programs have been ordered and JPL expertise will be established.

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TASK 4. SOLAR ARRAY AUTOMATED ASSEMBLY

The overall objective of Task 4 is to use the results and experience gained from Tasks 1, 2, 3, and 5 to fabricate solar arrays of 10% or better conversion efficiency at a price of \$0.50/watt or less at a rate of 500 megawatts per year with a 20-year operating life. Phase I (technology assessment) of this task has these specific objectives:

- To identify the requirements for economical manufacturing processes and facilities.
- To assess the current technology used in the manufacture and assembly processes that could be applied to solar arrays.
- To determine the level of technology readiness to achieve the high-volume, low-cost production.
- To propose processes for development.

A. TECHNICAL BACKGROUND

The manufacture of solar cells and arrays is presently performed by batch processes, primarily under the direct judgment and control of individual operators. Because of the limited quantities of solar cells and arrays produced, costs are high. The outstanding success of the semiconductor industry in applying automation serves as an illustration of the potential gains from high volume production. Automation accomplishes more than the obvious reduction in the amount of labor. In addition, automation causes a uniformity of processing which results in a more uniform product and produces a corresponding reduction in waste due to rejected product.

B. ORGANIZATION OF THE TASK 4 EFFORT

Task 4 is divided into five phases, occurring over a 10-year period of time; the phases are:

- I. Technology assessment.
- II. Process development.
- III. Facility and equipment design.
- IV. Experimental plant construction.
- V. Conversion to mass production plant (by 1986).

Figure 4-19 presents the overall schedule of this task and, for Phases I and II, identifies some of the activities these phases will include.

Many of the decisions that must be made during the Task 4 effort cannot be made independently. They will result from trade-offs with other decisions that are made both within the task and in conjunction with the other tasks of the Project. Task 4 has a particularly large number of interfaces, both within and outside of the task. Figure 4-20 shows the elements of Task 4 which require decisions. Elements joined by a line constitute an interface. Any given element cannot be totally resolved until its interfacing elements (connected by lines) are considered.

Figure 4-20 identifies the elements with the tasks involved by means of symbols. Since all of the elements shown involve Task 4, each has a circle (the symbol of Task 4). Elements which are also activities of other tasks have the additional task symbols superimposed upon the circles of Task 4. This means that, in addition to all the interfaces with other elements shown by lines, there are significant interfaces with the activities of the other tasks. This interface diagram is subject to updating as the Project develops.

C. TASK 4 CONTRACTS

Phase I contracts have been awarded to three contractors (Motorola, RCA, and Texas Instruments) to perform parallel efforts (Table 4-5). The three-contractor parallel effort philosophy was selected to obtain the broadest possible view of recommendations and conclusions upon which to base the contractual efforts of Phase II (Fig. 4-19). During Phase I these contractors will address the areas of defining the requirements for automation as applicable to solar cell manufacturing by evaluation of processes which are now used, and how these

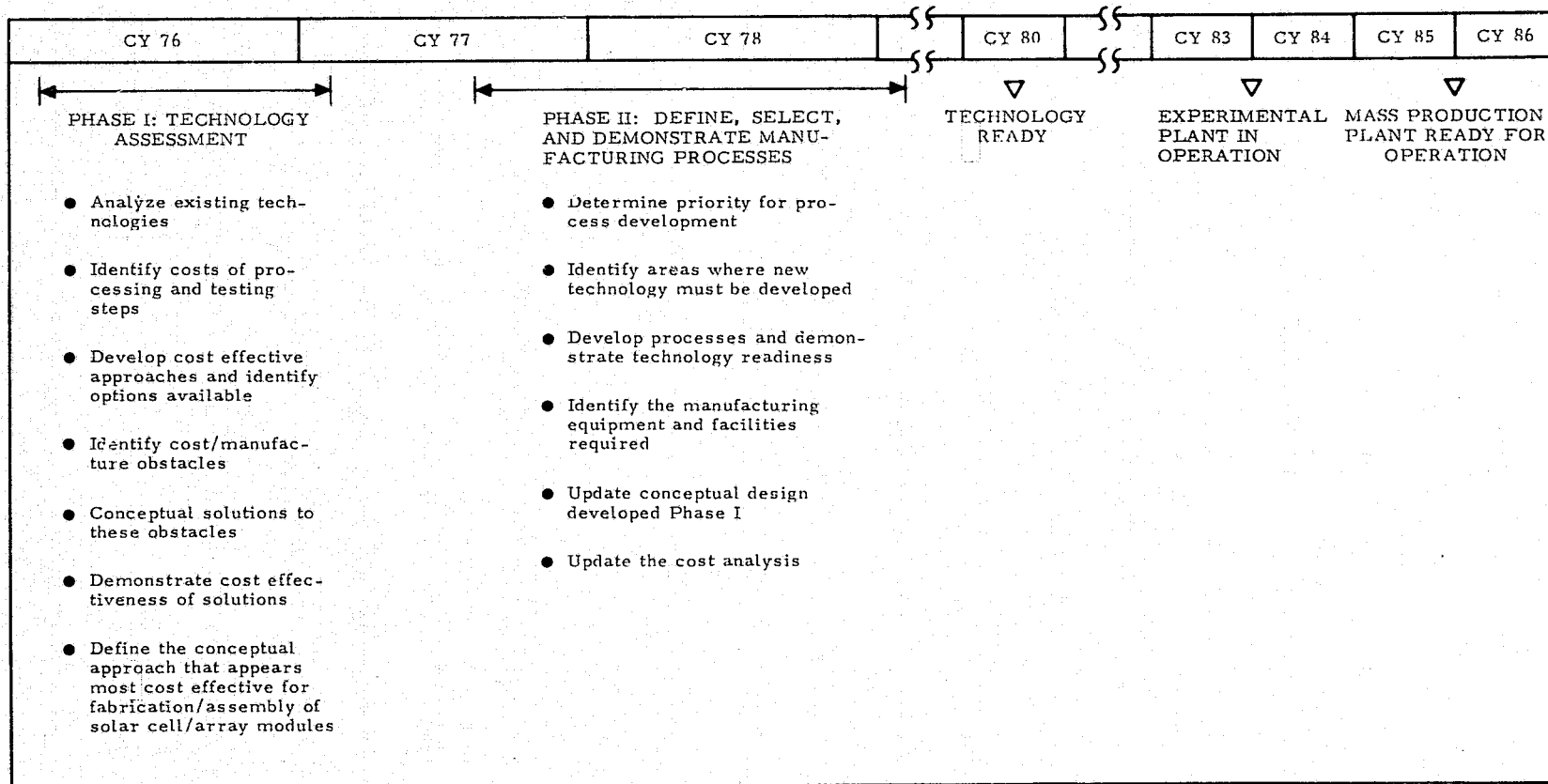


Fig. 4-19. Solar Array Automated Assembly Task schedule

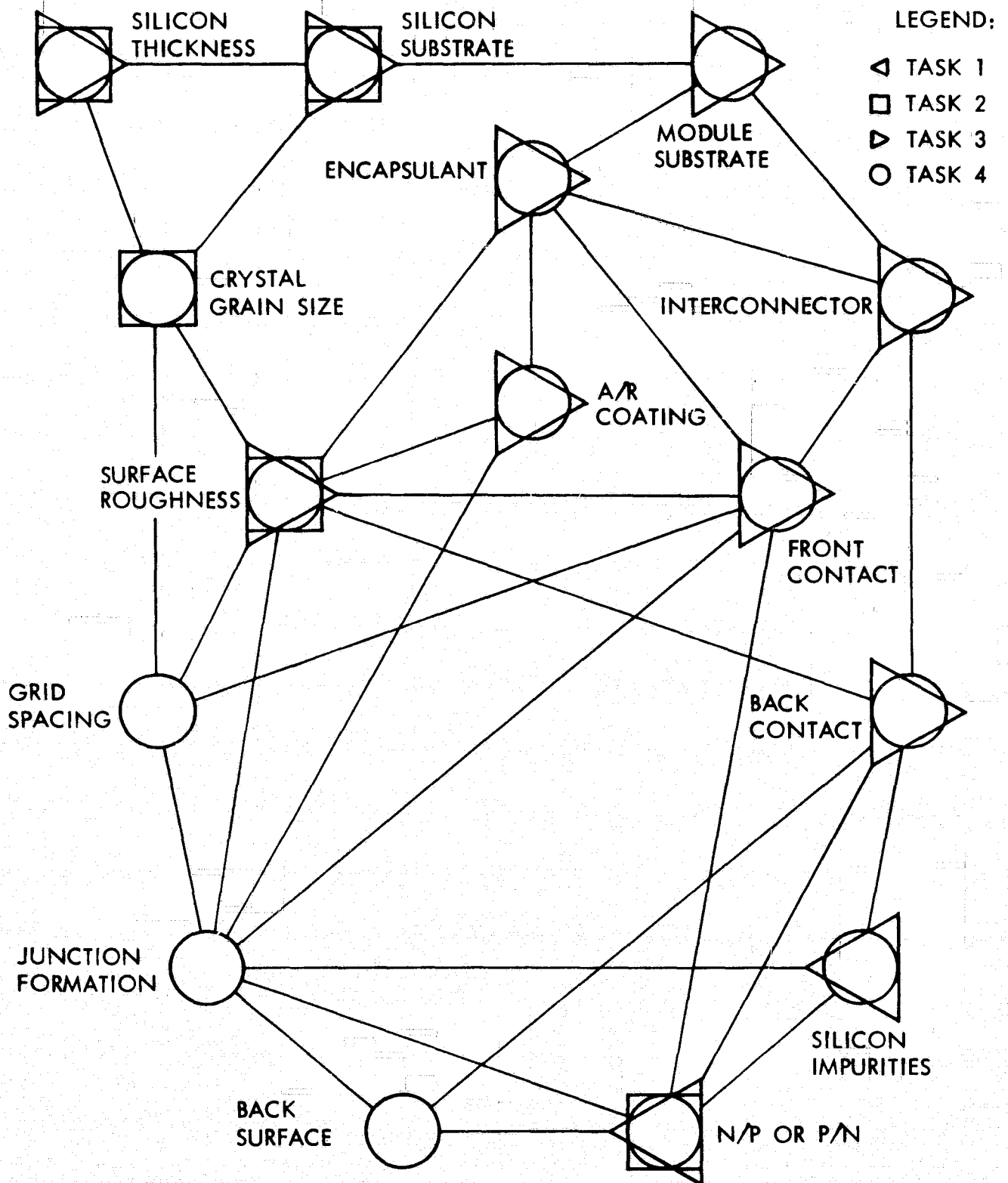


Fig. 4-20. Task 4 interfaces

Table 4-5. Task 4 contractors

Contractor	Technology Area
Motorola, Phoenix, Arizona	Manufacturing processes assessment
RCA, Princeton, New Jersey	Manufacturing processes assessment
Texas Instruments, Dallas, Texas	Manufacturing processes assessment
Simulation Physics, Burlington, Massachusetts	Electron-beam solar cell fabrication
Mitre Corporation McLean, Virginia	Array test evaluation
Texas Instruments* Dallas, Texas	Czochralski growth and wafering improvements
Solarex Rockville, Maryland	Array test evaluation
* Contract to be awarded in Spring of 1976.	

processes could be modified for high-volume, low-cost production. Cost analyses will be performed to provide economic guidelines to maintain an overall view of LSSA Project objectives.

The principal activities and avenues of inquiry to be undertaken by the three contractors in Phase I will be:

- Consideration of the various "forms" of silicon such as ribbon, sheet, wafers, etc.
- Consideration of the potential effects upon manufacturing if concentrators are used.
- Trade-off studies of new manufacturing technology.
- Studies of in-process testing requirements and procedures.

-
- Studies of solar cell interconnecting technology.
 - Studies of the applicability of state-of-the-art technology to an automated facility.
 - Detailed cost analyses of each potential manufacturing step.
 - Conceptual approaches for processing materials.

In addition the contractors will participate in technical reviews and a workshop to be held at JPL for representatives of government, industry, and the interested academic community.

Simulation Physics is carrying out a program to develop high rate, energy efficient solar cell processing techniques based on ion implantation and the elimination of all conventional thermal operations. Mitre and Solarex are evaluating array test methods.

D. TASK 4 TECHNICAL ACTIVITY

1. Manufacturing Processes Assessment - Motorola, RCA, and Texas Instruments

During the 1st Task Integration Meeting, each contractor (Table 4-5) presented the specific details of their individual approaches to the Phase I effort. Very shortly each will present a detailed program plan, which is the first contractual milestone. Although the basic objective is the same for all three companies, there are variations in their individual approaches. For instance, Texas Instruments is putting emphasis on silicon sheet which comes from a modified Czochralski process. Motorola is basing their effort upon the stated availability of low-cost silicon sheet being supplied by a new as yet undeveloped method. RCA is deliberately not favoring any type of silicon source.

An analysis has been made of the costs presently involved in the manufacturing of terrestrial solar modules. By considering the variations in design and manufacturing methods used by the different manufacturers, a composite design and method has been developed. This method is not followed by any current manufacturer although each step is used by at least one manufacturer

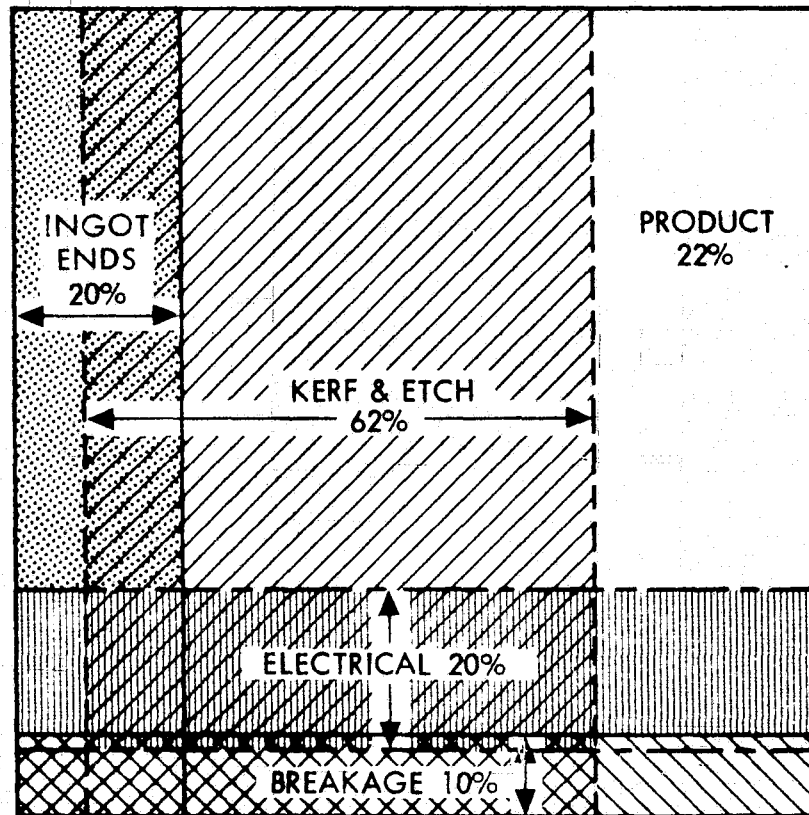
and could be used by all. As new methods develop in the course of this project, the influence upon cost change may be calculated using this state-of-the-art basic model.

At present, approximately 37 percent of the cost of a module is due to the refined silicon used as raw material for the solar cells. In current methods, about four-fifths of this silicon is wasted during processing. The most wasteful process at present is the slicing of the silicon after it has been grown into single crystal ingots. The kerf width is about equal to the slice thickness; consequently, half the material which reaches the slicing operation is wasted as small particles. Figure 4-21 shows the losses of silicon in graphic form. The individual categories are overlapped to illustrate the fact that the percentages lost at each operation apply only to the material which has survived the preceding operations and their losses. The figure illustrates, by proportionate areas, the increase in product survival if a specific loss is eliminated.

The economic model of the state-of-the-art includes the costs of materials, labor, supplies, and interest and depreciation on capital equipment. The manufacturing process is broken up into four subprocesses which can be and presently in some cases are performed in separate facilities or companies. These subprocesses are:

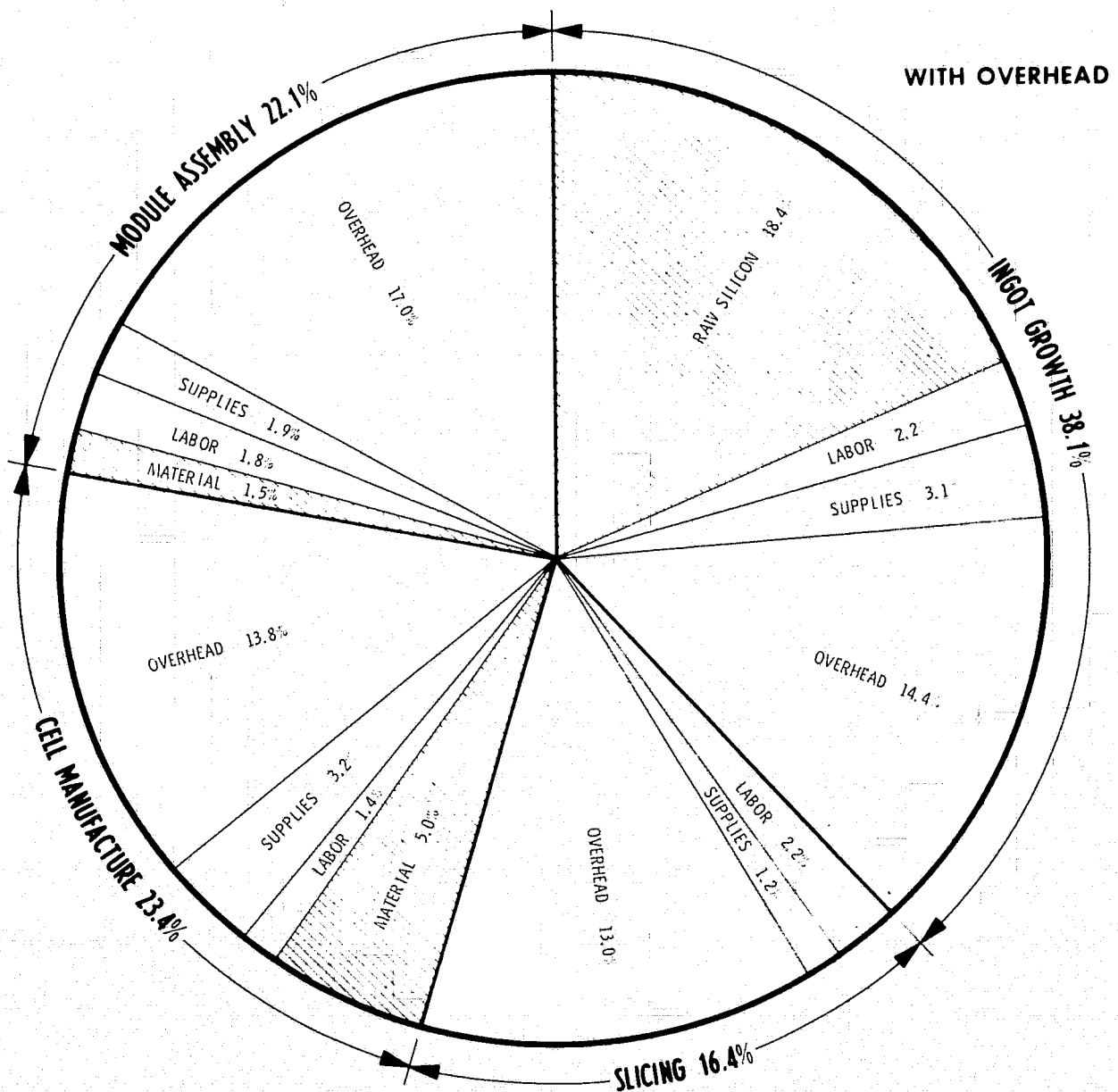
- Single crystal ingot growth.
- Silicon slicing.
- Solar cell manufacture.
- Assembly into solar panel modules.

Figure 4-22 shows graphically the proportionate costs of these subprocesses and their breakdown into cost elements. Overhead has not been proportioned or, if you prefer, the overhead has been uniformly applied in proportion to the costs. Present industry practice varies widely with regard to overhead and overhead distribution and depends upon several factors, one of which is whether or not other products are produced in the same facility.



1975 STATE-OF-THE-ART
0.010 INCH THICK CELL

Fig. 4-21. Silicon utilization



BASED ON SAMIS* COMPUTER PROGRAM (ID3)

* SOLAR ARRAY MANUFACTURING INDUSTRY SIMULATION

Fig. 4-22. Present state-of-the-art major manufacturing cost estimates

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2. Electron-Beam Solar Cell Fabrication - Simulation Physics

The objective of this program is to develop high rate, energy efficient solar cell processing techniques based on ion implantation and the elimination of all conventional thermal operations. Some specific objectives under this program include:

- No etching or cleaning operations.
- No batch process operations.
- No consumable materials other than those of cell components.

Figure 4-23 shows the principal parts of this concept in diagram form. The process is intended to be applicable to a wide variety of silicon forms. The direct processing energy will be less than 5 calories per square centimeter of solar cell area. The total processing time from silicon wafer to finished cell will be less than 30 seconds per square centimeter.

Cells have been made using a process sequence which includes conventional furnace heating. Cells like these will be used as standards for comparison of the pulsed-electron-beam-processed cells. Some cells have been made using the electron beam instead of the furnace. These cells did not have antireflective coatings on them but their power generating capability looks very promising. They have about three-fourths of the output of conventionally processed cells and are expected to be considerably better after antireflective coating has been applied.

During the next quarter the program will demonstrate the ability to produce cells without thermal processing. These cells will have an efficiency of more than 12 percent when the sun is directly overhead (11 percent efficiency above the atmosphere). This work will include the identification of the optimum parameters for the electron-beam annealing and sintering processes.

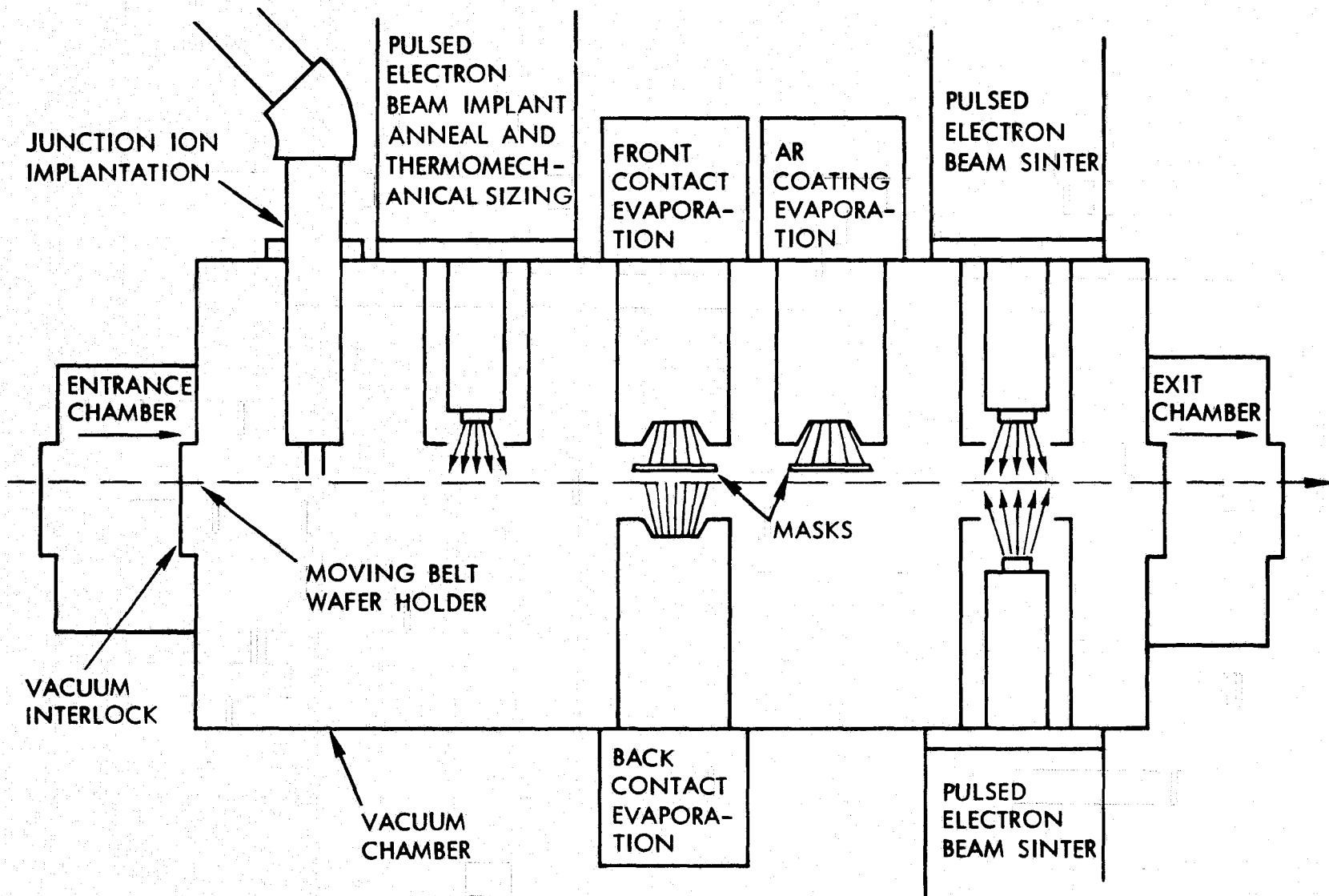


Fig. 4-23. Concept of pulsed processing for automated cell production -
Simulation Physics

3. Array Test Evaluation - Mitre Corporation

Work under this contract has been concluded and the final report is in process.

4. Array Test Evaluation - Solarex Corporation

Work under this contract has been concluded and the final report has been written.

PART V

LARGE-SCALE PRODUCTION TASK

The objective of the Large-Scale Production Task (LSP) is to produce silicon solar-array modules to support the ERDA Photovoltaic Test and Demonstration Project in progressively greater quantities and at progressively lower cost.

The task is expected to bring about improved designs in order to achieve production and cost improvements. The work will be carried out by production contractors, under Project sponsorship. In addition, whenever and wherever practical, this task will apply technology improvements achieved in other tasks of the Project to large-scale production, principally to aid in the achievement of task objectives, but also to test the new technology in the context of actual commercial manufacturing conditions.

Price goals for later module production are \$5 per watt by FY 1979, \$2 per watt by 1981, and \$1 per watt by FY 1983. Initial quantities to be procured are 46 kilowatts of state-of-the-art technology array modules and 130 kilowatts of advanced-technology modules (anticipated for delivery in FY 1977).

A. BACKGROUND

At the inception of the LSSA program in January 1975, the solar cell manufacturing industry in the United States was in decline. A solar cell production capacity of about 10 kilowatts per year, for use in space, had been reached in 1970, at the peak of the NASA program. Production of solar cells for spacecraft has been declining since. By comparison, the production of cells for terrestrial application was very low and increasing at a very slow rate. Only a few small companies were making terrestrial modules. These companies could be considered as offshoots of the large U.S. semiconductor industry. Silicon solar cells were made of semiconductor-grade silicon which has been unnecessarily expensive for large-scale terrestrial use. Large variations in

availability and price of pure silicon has been a feature of the dynamic semiconductor industry. As small consumers of silicon with limited resources, the smaller companies in the solar cell industry were occasionally subject to strong economic forces resulting in instability.

The market intervention of the Large-Scale Procurement Task of the LSSA into this industry should provide a strong stabilizing force and large cost reductions. An assured and growing market for solar modules should provide the incentives for private capital investment, process development, improved availability of raw materials at lower prices, and lower product costs from increased scale of production. Additional cost reductions will result when the developments generated by the technology development tasks of the LSSA Project are incorporated into the final product during the coming decade.

B. ORGANIZATION OF THE LSP EFFORT

The Large-Scale Production Task involves the periodic purchase of increasing quantities of solar arrays at decreasing unit prices and with the latest state-of-the-art technology. The arrays will be procured from industry on a commercial basis to meet performance specifications and environmental requirements for use in numerous and diverse ERDA tests and demonstrations.

Multiple contracts will be awarded to industry through a competitive bidding process for the production of large quantities of solar cell modules. A summary schedule for the LSP Task is shown in Fig. 5-1; a plan for the procurement is given in Fig. 5-2. The contracts will be awarded on essentially an annual basis for progressively increasing quantities of hardware. It is anticipated that the procurement schedule shown in Fig. 5-2 will be employed and, as indicated, two major subtask areas are identified for FY 1976: (1) the 46-kilowatt procurement of state-of-technology solar-array modules and (2) the 130-kilowatt procurement of advanced-design solar-array modules. Beginning with the 130-kilowatt procurement, small business concerns will be solicited through a set-aside procedure.

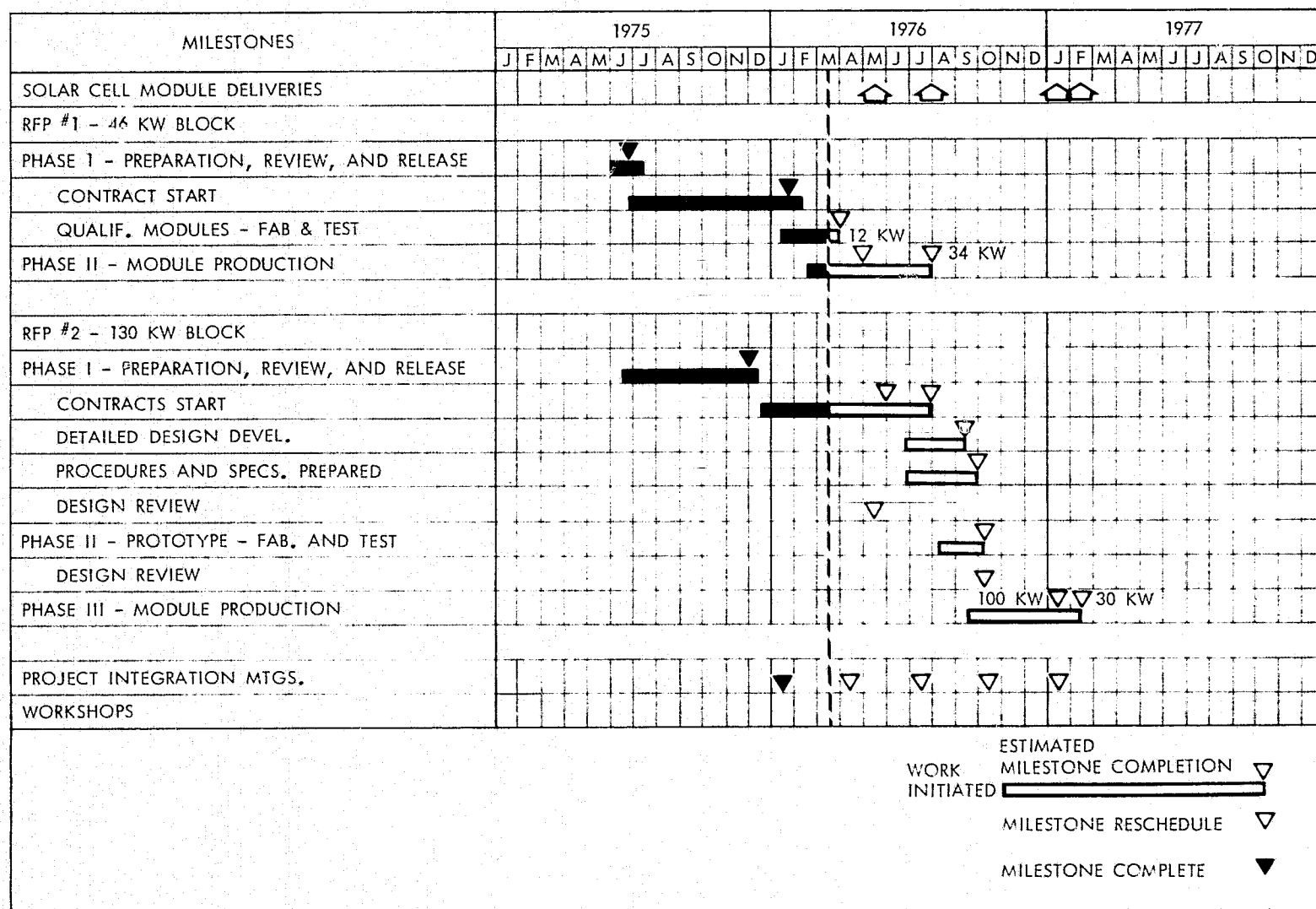


Fig. 5-1. Large-Scale Production Task schedule

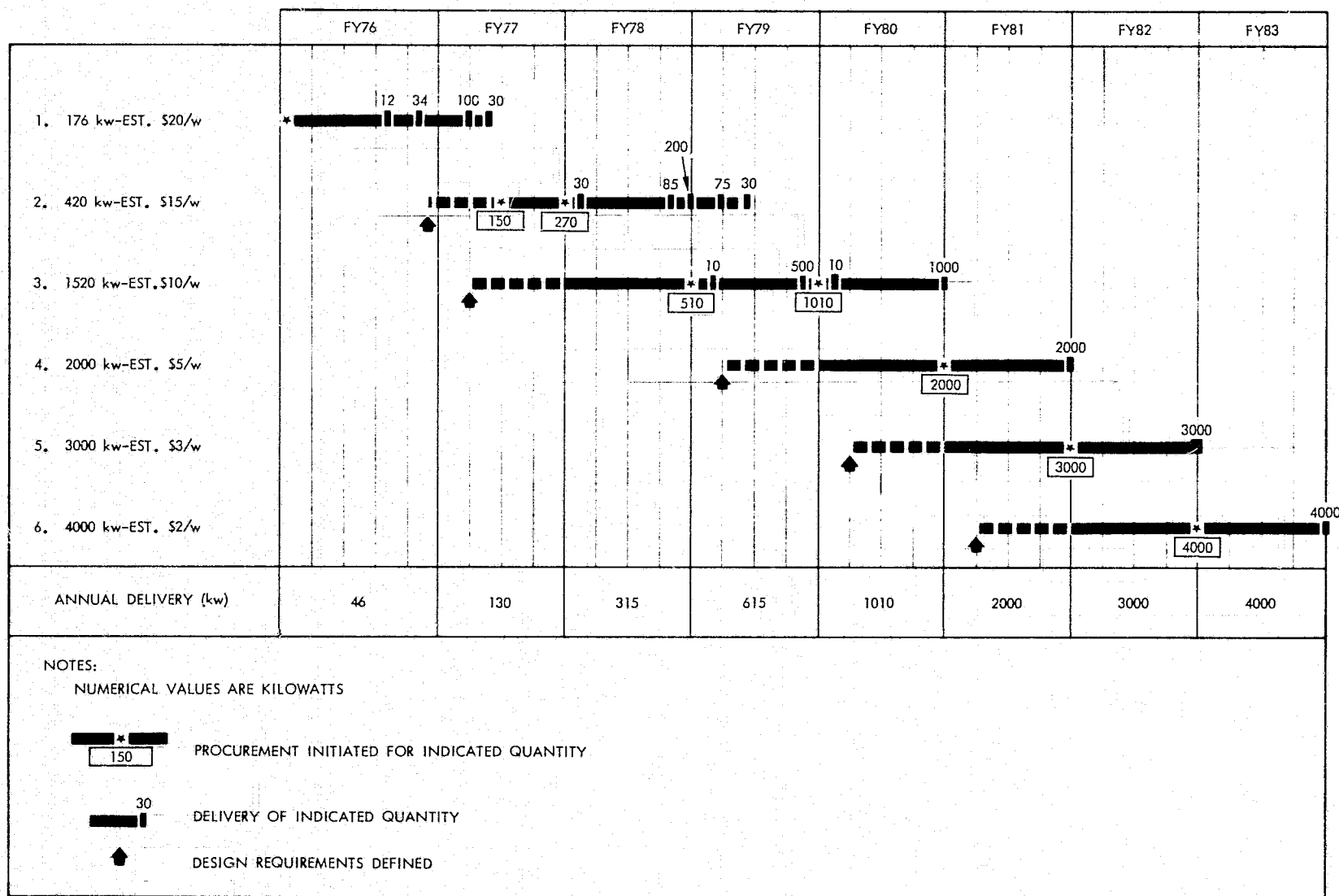


Fig. 5-2. Solar array procurement plan

The approach of the Large-Scale Procurement Activity was changed in 1975. Originally, solar modules were to be provided for a 200-kilowatt demonstration plant by 1977. It was planned to prepare solar-cell-grade material specifications leading to a prototype module in 1976. Production contracts would then be let providing 200 kilowatts by mid-1977. An RFP package for the early contract effort was prepared. However, in May 1975, the goals were changed and accelerated. ERDA adopted an earlier demonstration plan. As a result of restructuring of the ERDA demonstration plan, the existing RFP was terminated. Two RFP packages took its place. The first was for 40 kilowatts of state-of-the-art solar modules targeted for delivery starting in February 1976 and extending through July 1976. This quantity was revised later to 46 kilowatts to provide spares. This schedule for delivery to the demonstration program was very tight. It required expedited procurement from companies with manufacturing experience in modules of proven design to ensure meeting delivery schedules and performance. Initially, the modules produced would be used in applications requiring low power, such as for isolated installations of the Department of Defense. A longer range application would be for systems testing for ultimate tie-in of a photovoltaic power source to a commercial power grid.

The second RFP is for 130 kilowatts and will incorporate design changes to obtain a more uniform design providing greater flexibility in the demonstrations while encouraging further cost reductions. This procurement will be more widely solicited to the many companies presently preparing or extending manufacturing capability.

Another modification to the original concept is a plan to test samples from all procurement blocks. The RFP will require the contractors to perform certain tests. These tests will be repeated at JPL for confirmation and other tests added.

A Project Design and Test Activity was established in the Fall of 1975 for the purpose of (1) assisting in the development of solar array module design specifications and performance criteria and (2) assisting in technical interfacing with other ERDA program participants and coordinating in-house design and test activities.

The quality effort which has been initiated for the LSSA Project primarily supports the procurement of solar arrays and has three main objectives in addition to the normal quality tasks: (1) to evaluate the state-of-the-art of the commercial inspection systems presently employed by the commercial solar module manufacturers, (2) to evaluate and establish minimum inspection criteria and workmanship standards for use on future procurements, and (3) to establish and implement a problem failure reporting system that will yield field use data.

The RFP for the initial procurement specifies the temperature cycling and humidity requirements that the modules must meet. Qualifying the modules to these requirements is the responsibility of the supplier. At JPL, sample modules will be subjected to these environments and their performance will be evaluated. In addition, the modules will be exposed to other environments they are likely to meet during the ERDA demonstration program. These are humidity-freezing, rain-heat, salt fog, and fungus. Also, samples will be set up in racks at JPL as a field test in the Pasadena, California environment.

The 130-kilowatt procurement RFP is not limited to state-of-the-art modules of existing design. A contract period for design upgrading is provided and design criteria are given. Module designs are specified that will fit into a 4 by 4-foot subarray. Other RFP requirements are:

- 1) A minimum of 60 watts of power based on the 4 by 4-foot array.
- 2) One hundred thermal cycles from -40 to 110° C.
- 3) Five temperature cycles at high relative humidity.
- 4) One-hundred cyclical applications of structural loads.

The schedule for the 130-kilowatt procurement is:

- | | | |
|----|---|--|
| 1) | Detailed design developed | 2 months from contract start |
| 2) | Procedures and specification prepared | 2 months from contract start |
| 3) | Fabrication and test of prototype modules | 6 months from contract start |
| 4) | Module production | January 1977: 100 kilowatts
February 1977: 30 kilowatts |

C. LSP TECHNICAL ACTIVITY

1. Large-Scale Procurement Activity

A survey made early in the LSSA Project showed that there was no standardization of solar modules. Also, there were significant conflicting claims concerning module performance and price which needed to be understood. There was an urgent need for a standard method of module performance evaluation. It is intended that the Large-Scale Production Activity be beneficial in providing guidance and be a stabilizing force in these areas.

The Large-Scale Procurement Activity was essentially on schedule through January 1976. All contracts for the 46-kilowatt procurement had been awarded by January 1976. The following five companies were selected to produce the indicated stated quantities of solar array (see Frontispiece):

	<u>Kilowatts</u>
M7 International	3
Sensor Technology	8
Spectrolab	10
Solar Power	15
Solarex	10

The arrival at JPL of the first sample modules for test was delayed. The initial testing of these early modules has uncovered problems with the encapsulant. Solutions to these problems are being investigated with the contractors. The module delivery schedule has been delayed a few weeks. Production of modules will commence when these problems are resolved. The procurement will be completed in 6 months.

The RFP for the 130-kilowatt procurement was released to industry on December 15, 1975. Of the 130 kilowatts, 40 kilowatts are set aside for procurement from small business and 90 kilowatts from large business with stipulation that small business can bid on the total quantity of 130 kilowatts. Proposals

in response to the RFP were received February 2, 1976 and are in the evaluation process. It is expected that contract starting dates for the 130-kilowatt procurement will be in July 1976. A test plan for environmental test of the sample modules has been completed. Detailed test procedures for set A modules (temperature cycling and humidity test) have been completed also. Equipment and laboratory areas have been set up for these environmental exposures. A module evaluation area is ready. Electrical evaluation will be done with the Large-Area Pulsed Solar Simulator that has recently been installed and checked out. Physical inspection and module control areas have been made ready. Preparation for humidity-freezing and fungus testing should be completed by the time the sample modules arrive. Salt fog equipment and rain-heat testing equipment should be ready by April 1, 1976.

2. Design and Test Activity

Primary design and test technical accomplishments relate to the development of solar array design requirements and performance test criteria. Specific activities have centered in the following five areas: array configuration; module electrical performance; solar cell, module, and subarray interconnections; thermal design; and structural design.

Array configuration investigations have been conducted to evaluate module/subarray geometric requirements, solar cell packing efficiency versus module geometry and cell size, module ground handling requirements, and installation and removal, and similar considerations. Sample 4 by 4-foot subarray structures and various mockup module configurations have been designed and fabricated to allow experimental assessment of configurational and handling characteristics.

Module electrical performance activity is centered on module/array electrical requirements in the areas of series/paralleling considerations including analysis of "hot spot" effects and effects of mismatch in module and cell electrical characteristics and operating temperatures.

Solar cell, module, and subarray electrical interconnections are an important element of solar array lifetime and reliability. Various module electrical termination schemes are currently being fabricated in preparation for environmental testing evaluation and the generation of future electrical termination requirements.

Thermal design activity includes analysis and testing directed at understanding module/solar array thermal performance considerations, thermal design criteria, and test methods. Thermal analyses and tests of various solar array module designs have been conducted and measurements have been made to accurately determine thermal photo-optical properties. Experiments conducted during preliminary thermal tests indicate that module open circuit voltage (V_{oc}) and short circuit current (I_{sc}) may provide a reliable measure of solar cell temperature when used together in the following relationship:

$$\text{Cell temperature} = a + bV_{oc} + c\log_{10}(I_{sc})$$

Constants a, b, and c are calibrated during tests in which thermal gradients within the module are minimized or eliminated. Such an indirect measurement technique is very desirable because of the general difficulty in attaching thermocouples directly to encapsulated solar cells.

Structural design activity includes analysis and testing directed at understanding module/subarray structural loading criteria and test methods. An automatic module structural loading machine has been designed and fabrication initiated. Future tests will include determination of the load-carrying capability and load-cycle-life characteristics of various module designs.

In addition to the in-house investigations described above, close liaison is maintained with the NASA Lewis Research Center demonstration activities, the Sandia Laboratories system analysis activities, and the demonstration activities of the Department of Defense. Design requirements emanating from these studies are incorporated into the solar array requirements activity on a continuous basis. Discussions with module manufacturers and potential and past photovoltaic users also provide valuable information which is incorporated into solar array requirements.

3. Quality Assurance Activity

The preliminary evaluation of commercial solar module manufacturers commercial inspection systems was undertaken during the review of the 40 kW proposal and on subsequent site visits. It was found that the inspection systems ranged from very minimal systems to ones almost equal to those for aerospace applications.

Two solar modules from each of six commercial suppliers were procured and inspected in the "as received" condition to determine the present state-of-the-art workmanship standards utilized by each of the suppliers. The workmanship evidenced by the panels paralleled the results found in relation to the inspection systems. Some modules had very little uniformity in workmanship and other panels were of almost aerospace quality.

The results of the inspection system evaluations and the solar module inspection, both the initial two panels and the subsequent inspections at each of the suppliers will be used to formulate minimum inspection criteria and workmanship standards for future procurements so that eventually solar module hardware of uniform quality from supplier to supplier can be obtained.

A problem/failure reporting system has been developed that has two main objectives: (1) to obtain field data from site installations, in real time, on the solar modules produced during the 40 kilowatt and subsequent procurements and (2) to provide a data bank where the information can be stored and easily obtained when required. It is intended to use the data bank to correlate information on field problems or failures with the inspection reports of the modules obtained during manufacture at each of the suppliers. In this way the inspection criteria and workmanship standards employed by each of the suppliers of commercial solar modules can be evaluated for their applicability and subsequently changed where necessary. The information will also assist in preparation of the minimum criteria and standards previously discussed.

4. Future Activities

- 1) Future activities will assist in the development of module configuration requirements with emphasis on requirement differences associated with the general solar array applications:
 - Universal low-cost arrays typical of the majority of present day applications.
 - Residential arrays which incorporate architectural features appropriate for residential dwellings.
 - Lightweight arrays which address needs for compactness and mobility typical of military and similar applications.
- 2) Preparations are being made for receiving sample modules, inspecting, electrical evaluation, and environmental tests. Designs of the field test and rain-heat test are underway. The test equipment will then be fabricated and installed. Test procedures will be generated for these plus the fungus, salt fog, and humidity-freezing tests. Future activities will study requirements for lightning protection and diode circuit protection within solar array modules.
- 3) Contract monitoring activity started in January and will be increased in the next quarter. Plant visits will be made to check progress and assist in performance evaluation and standardization. In-house monitoring activities include liaison between contractors, JPL and LeRC. An accountability system for all modules will be set up over the next several months.
- 4) Intensive proposal evaluation activity will be carried on for the 130-kilowatt procurement with a target date for completion by April 1976. Completion of contract negotiations and releases are scheduled for June 1976.
- 5) Preparation of the 150-kilowatt RFP for 1977 will receive increasing attention with a target release date of early 1977. Technological and administrative improvements resulting from the experience of the first two procurements will be incorporated in this RFP.